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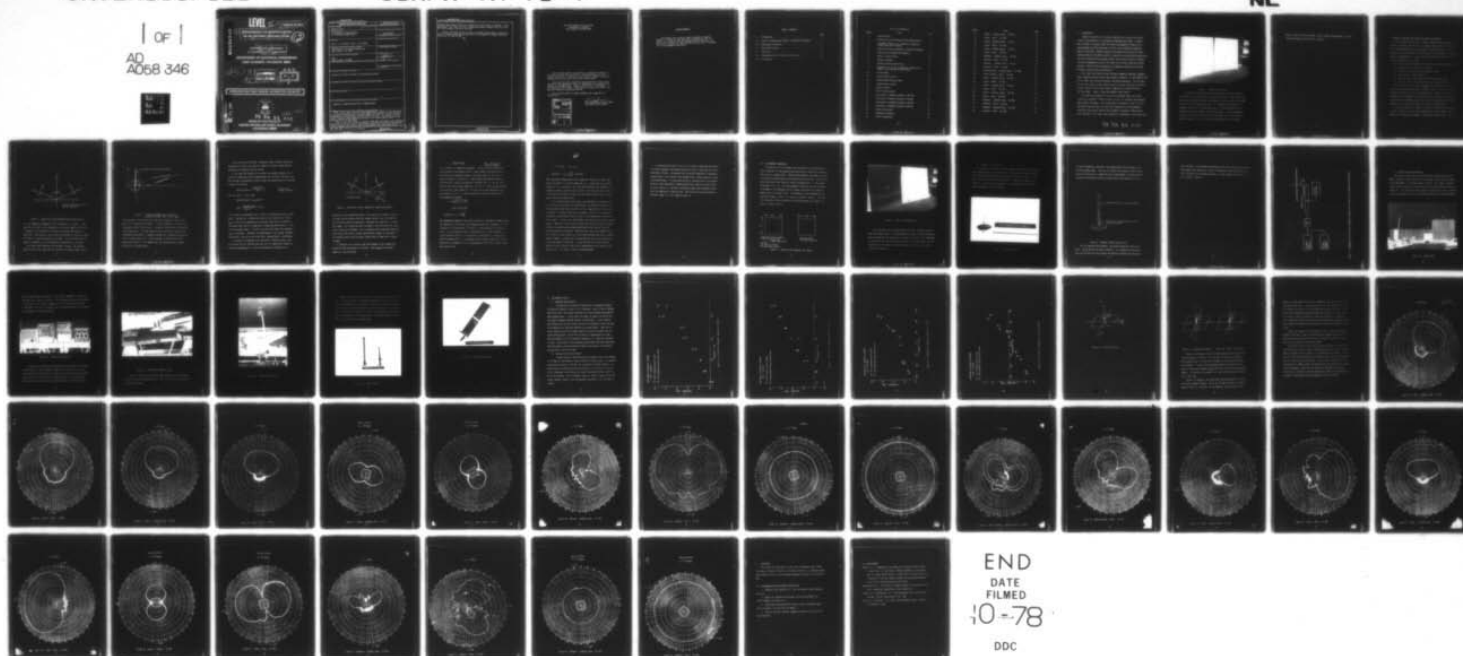
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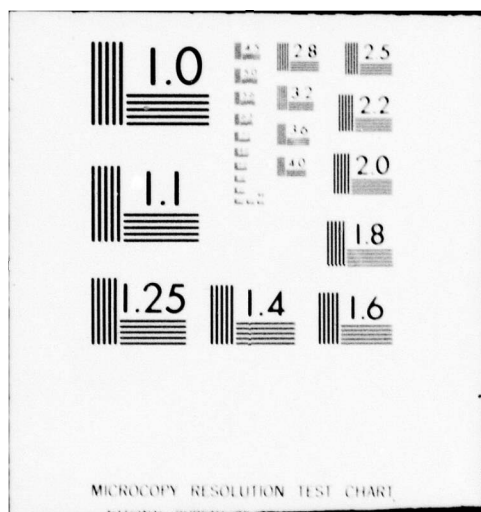
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PERFORMANCE OF GRAPHITE EPOXY
AS AN ANTENNA GROUND PLANE.

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CAPTAIN JOHN E. ERICKSON
LT COLONEL OSCAR D. GRAHAM

DEPARTMENT OF ELECTRICAL ENGINEERING
USAF ACADEMY, COLORADO 80840

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graphite epoxy sheets and also an identically sized sheet of aluminum. These measurements were made with both monopole and dipole antennas and also with a UHF blade antenna from an F4 aircraft.

Results show that the 50 ply sheet of graphite epoxy behaves identically with an aluminum ground plane when used with a monopole or dipole receiving antenna at 370 and 837 MHz.

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Editorial Review by Lt Col Elser
Department of English
USAF Academy, Colorado 80840

This research report is presented as a competent treatment of the subject, worthy of publication. The United States Air Force Academy vouches for the quality of the research, without necessarily endorsing the opinions and conclusions of the author.

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I. INTRODUCTION

Composite materials are finding increasing use as parts of aircraft structure due primarily to the weight advantages they offer. As their use increases, a concern exists over the electromagnetic effects of replacing metal aircraft structures with the lesser understood composite material structure. Numerous antennas are mounted on aircraft and these antenna often use the metal aircraft structure as an electrical ground plane. The metal structure also strongly affects the aircraft's ability to shield electrical equipment as well as the radar cross section that the aircraft displays. How will the increased use of composite material for aircraft structure affect these considerations?

This study was limited to one particular composite material, graphite epoxy composite material number HMF-133/34 by Fiberite. In this material 50% of its fibers are oriented vertically and 50% horizontally. Two five foot by five foot sheets of this material were set up and cured for use in this study by the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. Figure 1 shows the graphite epoxy sheets.

Each sheet was composed of 50 plies of graphite fibers and, after curing, this produced a sheet of about 1/4 inch in thickness and weighing approximately 50 pounds. The second sheet was obtained so that if it was determined that one sheet was partially transparent to electromagnetic radiation, both sheets could be used together to produce a double thickness (100 plies) for further investigation of transparency, skin depth, etc.

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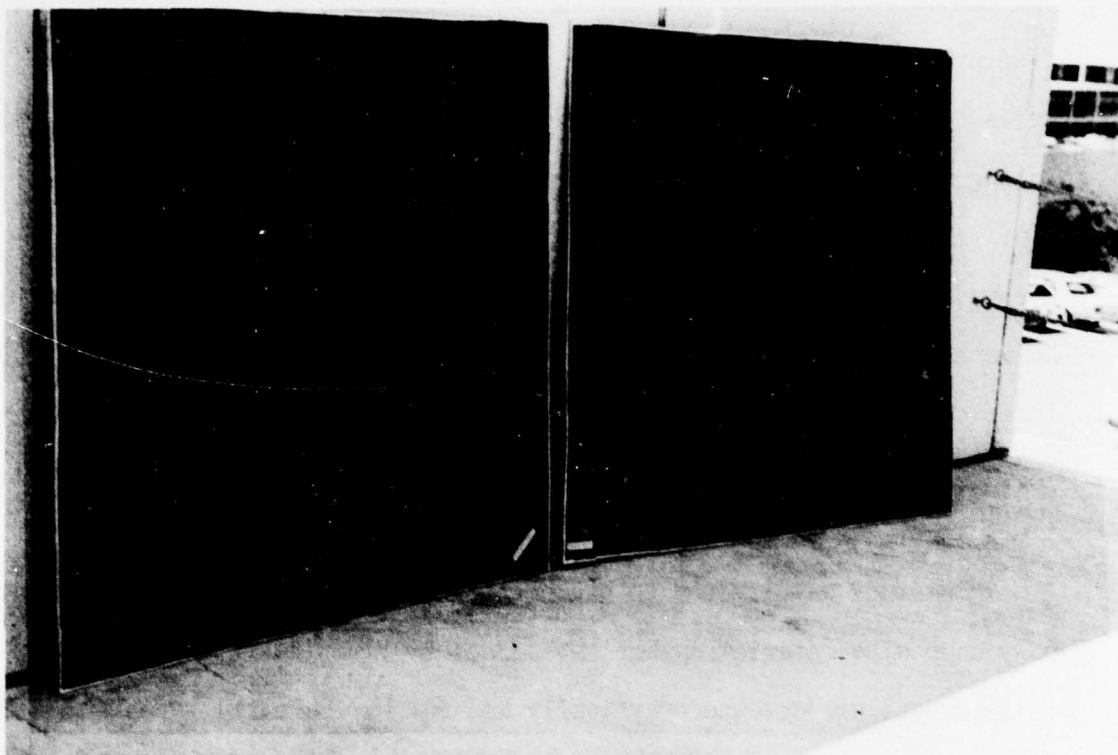


Figure 1. Graphite Epoxy Sheets

In addition to being limited to graphite epoxy composite material, this study was also restricted in several other ways. Signal source and antenna considerations limited the frequencies tested to 370 and 837 MHz. Two types of measurements were made: 1) Impedance measurement of a monopole antenna over a ground plane and 2) Antenna pattern plots of monopole and dipole antennas over a ground plane. These measurements, therefore, relate most directly to the consideration of the ability of graphite epoxy to act as an electrical ground plane for an antenna.

However, they also have relevancy to the related considerations of shielding effectiveness and radar cross sections.

II. THEORY OF GROUND PLANE EFFECTS ON ANTENNA PERFORMANCE

We will examine several basic concepts separately then put them together to visualize the affects of an antenna transmitting (or receiving) over a finite ground plane of an imperfect conducting material. These concepts are well documented in the literature so no extensive or rigorous proof is attempted here. A brief review of the theory involved for the following situations is in order:

- (1) Plane wave reflecting from an infinite perfectly conducting plane.
- (2) Image theory as it applies to antennas.
- (3) Plane wave reflecting from an imperfect plane.
- (4) Skin depth in a good conductor.
- (5) Antennas over a finite perfect conducting ground plane.
- (6) Antennas over a finite imperfect conducting ground plane.

When a plane wave is incident obliquely on a conduction plane it is necessary to consider separately two special cases. In order to be brief only one of these cases will be considered here. The two cases are described by the orientation of the electric vector and may be described as vertically or horizontally polarized. Since a large portion of aircraft antennas are vertically polarized, this case will be developed.

In the case depicted in figure 2, \vec{E}_i and \vec{E}_r (incident and reflection electric section) will have the instantaneous directions shown. At any boundary the tangential component of the electric vector must be zero,

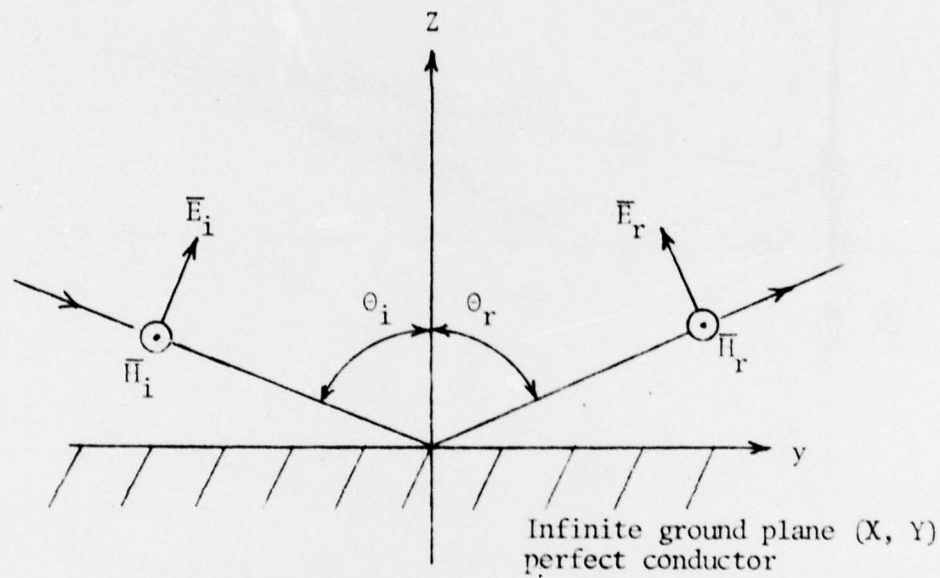


Figure 2. Reflection of Wave Having Vertical Polarization

i.e. the tangential component of \vec{E} is continuous at a surface. Since the electric field is zero everywhere in a perfect conductor then the y component of \vec{E}_i and \vec{E}_r must be equal in magnitude and opposite in direction. Since energy is not stored or dissipated in a perfect conductor there is a total reflection of the wave. It can be shown that the angle of incidence, θ_i , and the angle of reflection, θ_r , are equal.

This leads quite naturally into the next concept. The incident electric vector, \vec{E}_i , could have as its source a current element (basic

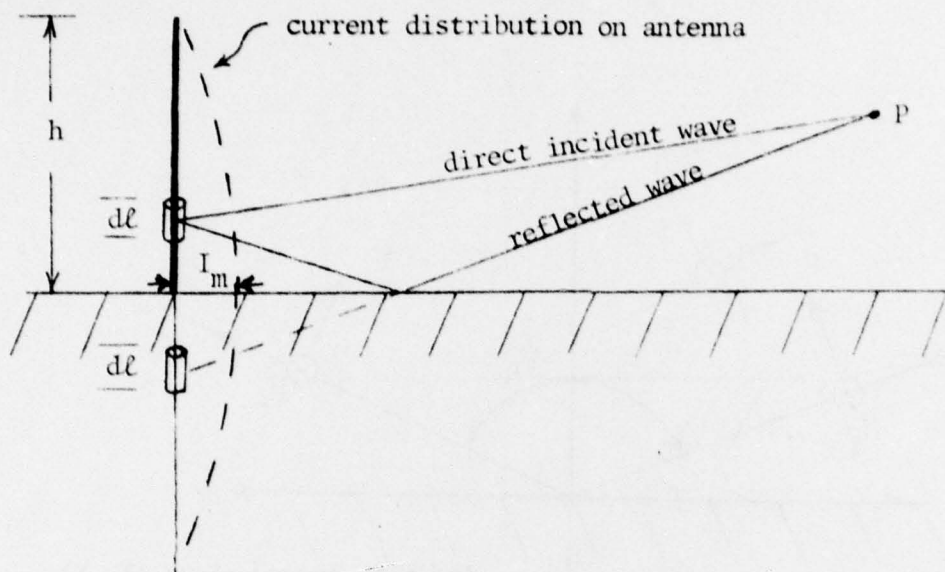


Figure 3. A Monopole Antenna over a Perfectly Conducting Ground Plane and its Image.

building block in calculating the total electromagnetic field at some point, P.) as depicted in figure 3. It can be shown that the total electromagnetic fields at any point, P, in the far field can be calculated by using image theory. In other words the fields at point P would be the same whether generated by a monopole antenna over a perfectly conducting infinite ground plane or by a dipole antenna in free space with the ground plane removed. This demonstrates the important part a ground plane plays in antenna theory.

If the current distribution is known, the power radiated through the hemispherical surface may always be found by straight forward methods, although the integration may be tedious.

If one takes the example of a quarter-wave monopole antenna over a perfectly conducting infinite ground plane and calculates the power radiated through a hemispherical surface above the ground plane the following results are obtained.

$$\text{Radiated power} = \frac{0.609\eta I_m^2(\text{eff})}{2\pi}$$

Ref. p. 332
Jordon & Balmain

for free space $\eta = 120 \pi$ ohms

$$\text{Radiated power} = R_{\text{rad}} I_m^2(\text{eff})$$

$$R_{\text{rad}} = \frac{\text{Radiated power}}{I_m^2(\text{eff})} = 36.5 \Omega$$

for a quarter wave monopole over a perfectly conducting infinite ground plane. Consider for a moment the affect on the radiation resistance, R_{rad} , if the fields impinging on the ground plane were not completely reflected either due to an imperfectly conducting ground plane or a finite sized ground plane. In either case one would expect the impedance, R_{rad} , to decrease. Therefore, the measurement of the antenna impedance should give a clue as to how effectively a ground plane is performing.

If a plane wave impinges on an imperfectly conducting plane, part of the wave will be reflected and part will be transmitted through the plane and (depending on σ) will be dissipated or attenuated as it

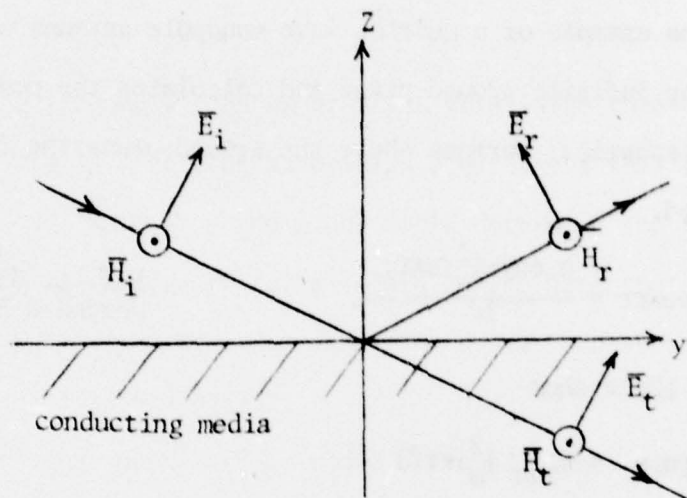


Figure 4. Reflection from an Imperfectly Conducting Boundary

progresses in the conducting media. As in the case of figure 4 the direct wave from an antenna would not change; however, the reflected portion would be reduced in amplitude. The angle of reflection, θ_r , would not change. This would mean that the phase of the reflected wave at any point P should be unchanged. For a reasonably good conducting plane one would expect only minor, perhaps imperceptible changes in the shape of the antenna pattern with the major change being in magnitude or signal strength.

If shielding is of interest then what happens to the transmitted portion of the wave becomes of interest. The propagation constant, gamma (γ), can be written:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}$$

Ref: pp. 126, 127
Jordon & Balmain

If $\sigma = 0$ the γ is completely imaginary. In this case the transmitted wave would not be attenuated at all. Only a phase shift would occur as the wave passes through the media. This would apply to the case of a perfect insulator or dielectric. The dividing line between conductors and dielectrics could be considered to be when $\sigma/\omega\epsilon = 1$. We are interested in the case of good conductors. If $\sigma/\omega\epsilon \gg 1$ then the media would be considered a good conductor. For the case of wave propagation in a good conductor ($\sigma/\omega\epsilon \gg 1$) one may derive the following expression for the propagation constant:

$$\gamma = \sqrt{(j\omega\mu\sigma)(1 + j \frac{\omega\epsilon}{\sigma})}$$

$$\approx \sqrt{j\omega\mu\sigma} = \sqrt{\omega\mu\sigma} / 45^\circ$$

$$\text{therefore } \alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}}$$

The attenuation constant α will give a clue as to the depth of penetration. The amplitude of the fields in a propagating wave will attenuate at a rate indicated by the expression $e^{-\alpha z}$ where z is the propagation distance in meters, a term frequently used to indicate how far a wave propagates in a good conductor before it is dissipated is referred to as skin depth or depth of penetration, δ . δ is defined as that depth in which the wave has decreased or attenuated to $1/e$ or approximately 37% of its original value. This implies that

$$e^{-\alpha\delta} = \frac{1}{e} \quad \text{or} \quad \alpha\delta = 1$$

$$\text{therefore } \delta = \frac{1}{\alpha} \cong \sqrt{\frac{2}{\omega\mu\sigma}} \text{ in meters}$$

Note that when frequency goes up or sigma gets large then δ gets small. Unless the media is a ferrous material, $\mu \cong \mu_0$. Note that for a perfect conductor $\delta = 0$. Knowing σ and ω one could determine the thickness of a composite material necessary for a shield. Also note that the smaller δ is the better reflector of radio waves the media becomes and as a consequence the better ground plane.

In all antenna applications where a ground plane is used some practical limits are placed on the ground plane. An infinite perfectly conducting ground plane would obviously reflect completely the fields from an antenna. In making laboratory measurements very little is gained in extending a ground plane beyond a radius of the antenna more than three wave lengths. In many cases measurements must be made with smaller ground planes. When care is exercised to insure that adverse resonant configurations are avoided smaller ground planes may be used without seriously affecting the data collection. Obviously the size of the antenna being used as well as wave length are factors that determine how large a ground plane is needed. In many practical applications one is stuck with whatever ground plane is available. A good reference for a more complete analysis of the affects of the size of ground plane can be found in the works of Dr. J. E. Storer listed in the Bibliography.

In analyzing the works of Dr. R. W. P. King it seems that the affects on antenna impedance and antenna patterns in the far field may be briefly analyzed as follows. An antenna over an infinite imperfectly conducting ground plane is very similar to an antenna over a finite perfectly conducting ground plane. It would seem logical to conclude that if the ground plane was both imperfectly conducting and finite that the results would be quite similar to a perfectly conducting ground plane somewhat smaller than the imperfectly conducting one. The relative size would depend on how much larger ($\sigma \gg \omega\epsilon$) sigma was than $\omega\epsilon$.

III. MEASUREMENT TECHNIQUES

The objective was to determine any differences in the electromagnetic properties of the graphite-epoxy material as compared to aluminum when used as a ground plane. Therefore measurements were made with antennas mounted on ground planes constructed of both materials. Both ground planes were made with identical surface configurations - a flat square measuring 5 ft x 5 ft. The only geometric difference was the difference in thickness; the aluminum was 0.125 inches thick while the composite material was 0.25 inches thick. The thickness of the aluminum was not important, however, since it is close to a perfect conductor. The physical dimensions of the aluminum and the graphite-epoxy test samples are shown in figures 5 and 6.

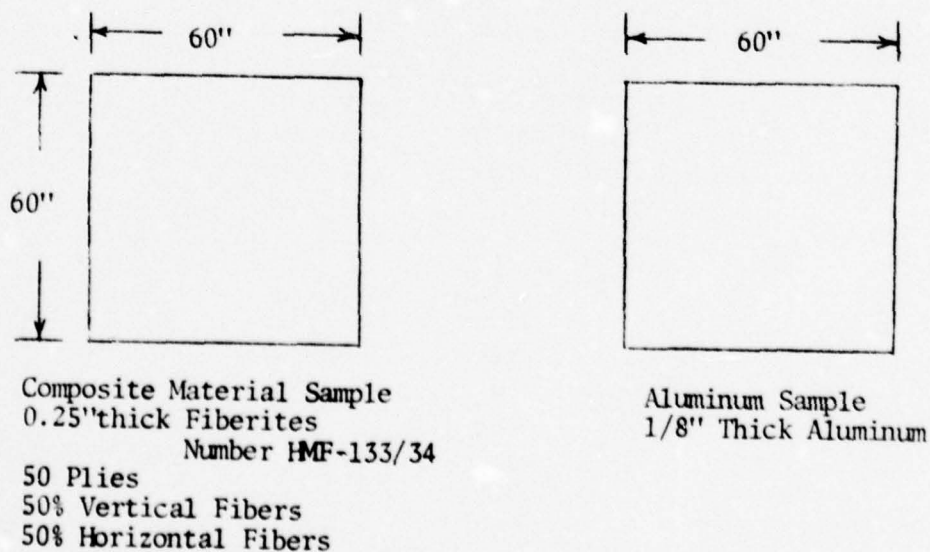


Figure 5. Composite and Aluminum TEST Samples

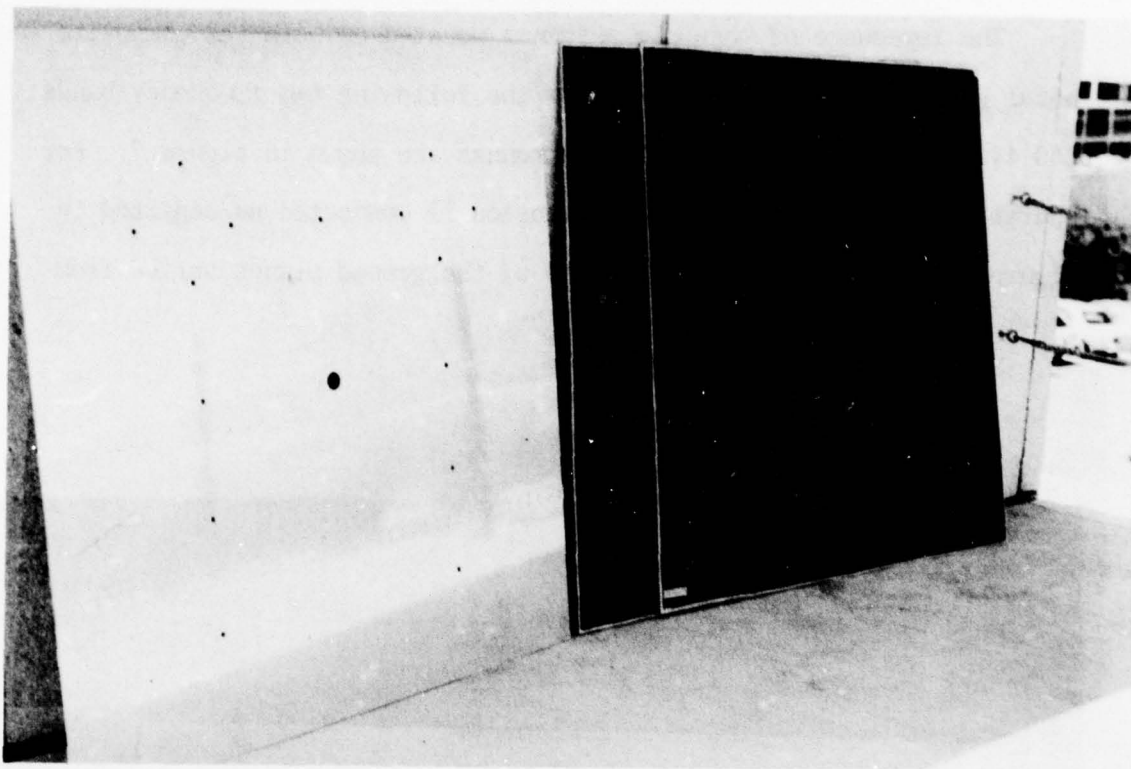


Figure 6. Photo of Ground Planes

Two different types of measurements were made: impedance measurements and antenna plots. Each measurement was made on both ground planes while keeping the test conditions as similar as possible. By attempting to insure that the only difference between sets of measurements was the ground plane, any change in measured parameters would be due to the ground plane material.

A. Impedance Measurements

The impedance of monopole antennas mounted on both the composite and metal ground planes was measured for the following two frequency bands; 360-440 MHz and 780-900 MHz. The antennas are shown in figure 7. For operation in the lower band the extension is connected as depicted in figure 8. The electrical dimensions of the ground planes varied from 1.83λ at 360 MHz to 4.5λ at 900 MHz.

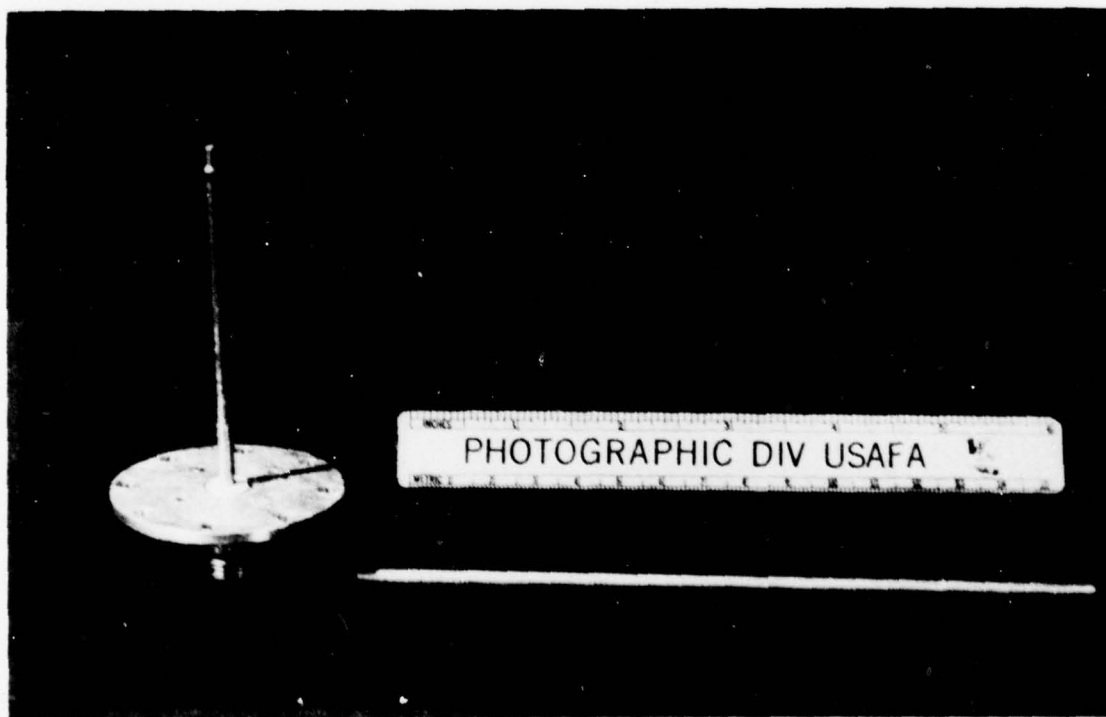


Figure 7. Monopole Antennas

At these frequencies, therefore, the ground plane will not behave as an infinite ground plane. This does not affect the validity of the results, however, because only a comparison type of measurement is being made with the metal and composite material ground planes being identical in size.

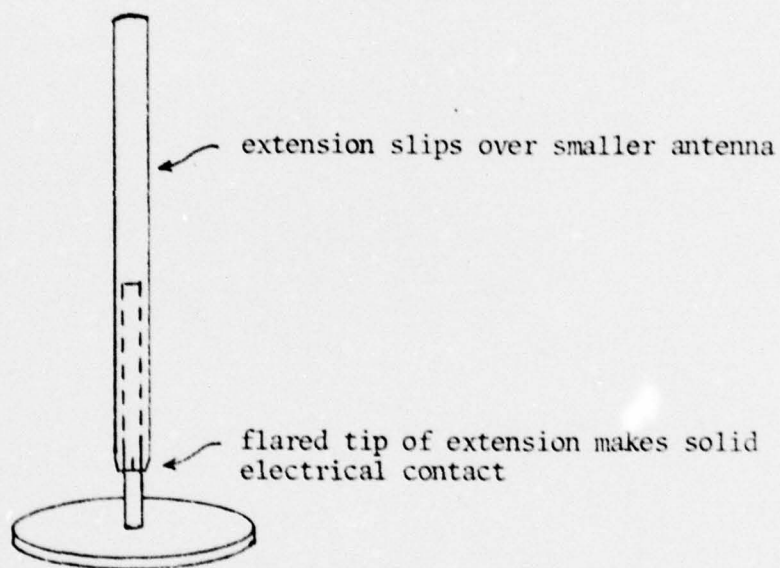


Figure 8. Monopole Antenna Construction

For the impedance measurements, the ground planes were placed outdoors facing skyward on wooden sawhorses. All equipment and personnel were placed under the ground plane and therefore unwanted perturbations

were minimized. The impedance was measured using the slotted line technique. Measurements were taken over a range of frequencies centered upon the resonant frequency of the monopole antenna. A block diagram of the test set-up is shown in figure 9.

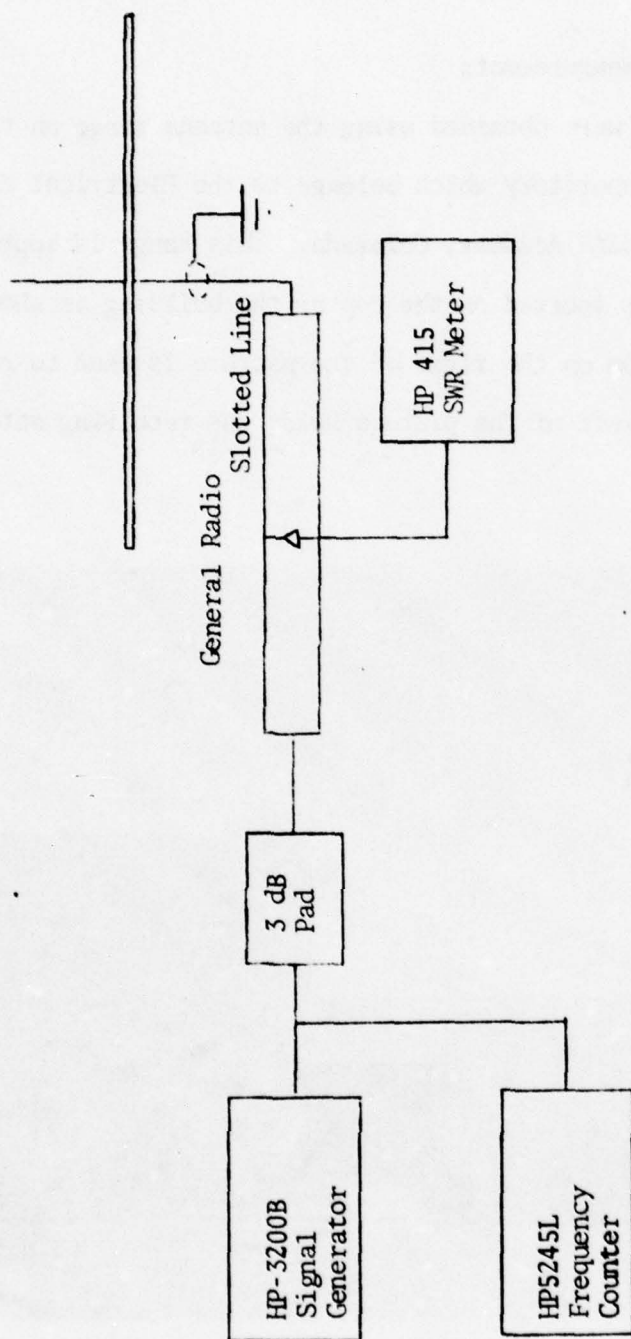


Figure 9. Impedance Test Set up for Monopole Antennas over Composite and Aluminum Ground Planes

B. Antenna Pattern Measurements

The antenna patterns were obtained using the antenna range on the Radio Frequency Systems Laboratory which belongs to the Electrical Engineering Department at the USAF Academy, Colorado. This range is approximately 60 feet long and is located on the top of the building as shown in figure 10. The small boom on the right of the picture is used to radiate and the long boom on the left of the picture holds the receiving antenna

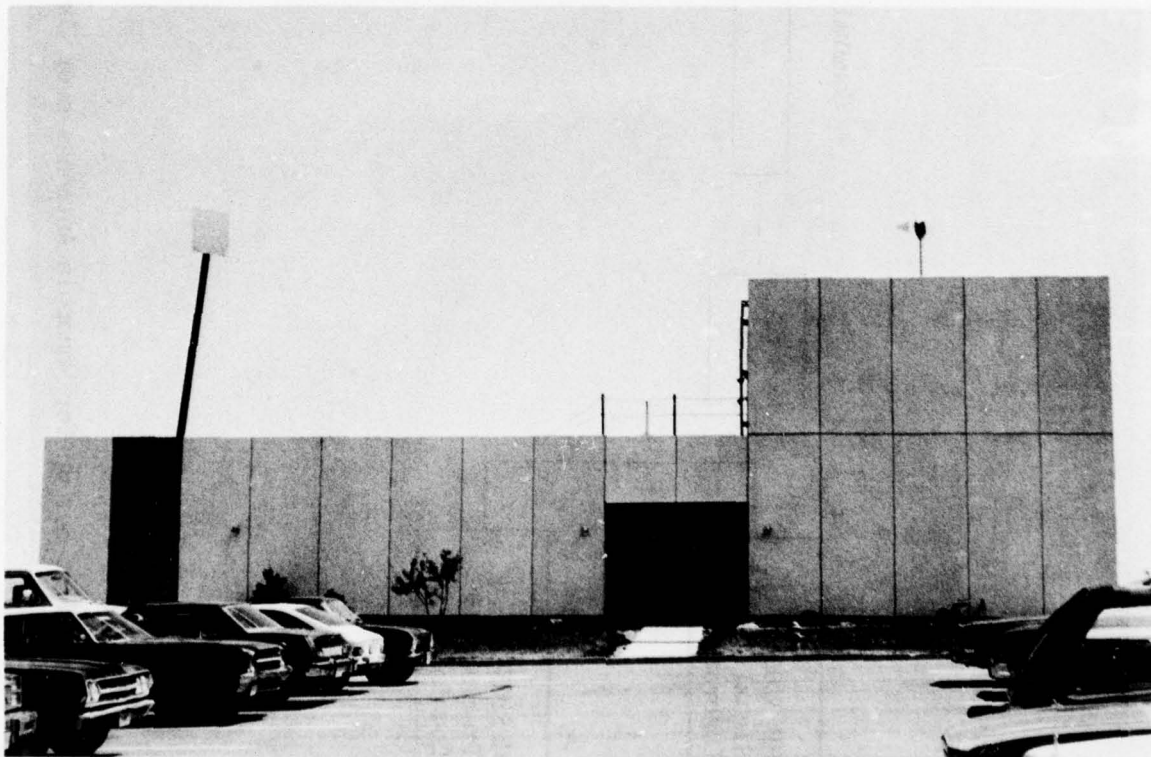


Figure 10. Antenna Range

and the ground plane being tested. The control equipment is inside the building and is shown in figure 11. This equipment controls polarization of both transmit and receive antennas as well as controlling rotation around 360° of the receive antennas boom. Antenna patterns can be plotted in rectangular or polar coordinates.

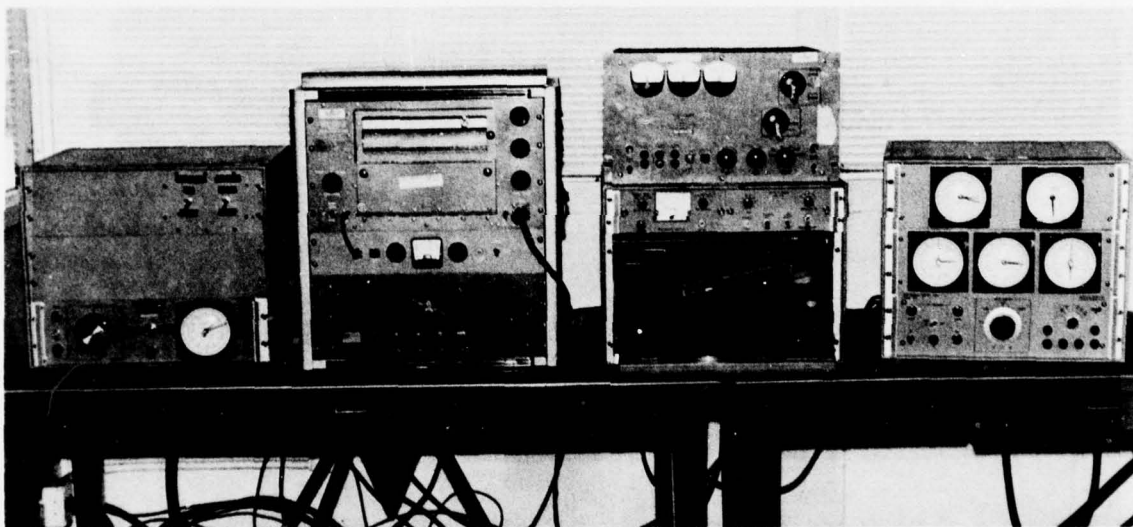


Figure 11. Antenna Range Controls

A technique for mounting the ground planes to the boom was designed and constructed. This technique (figure 12) consisted of a specially constructed wood frame which was attached to the ground plane using nylon bolts and was also attached to the mounting plate of the antenna boom. Nylon bolts were used to reduce any perturbations of the energy field.

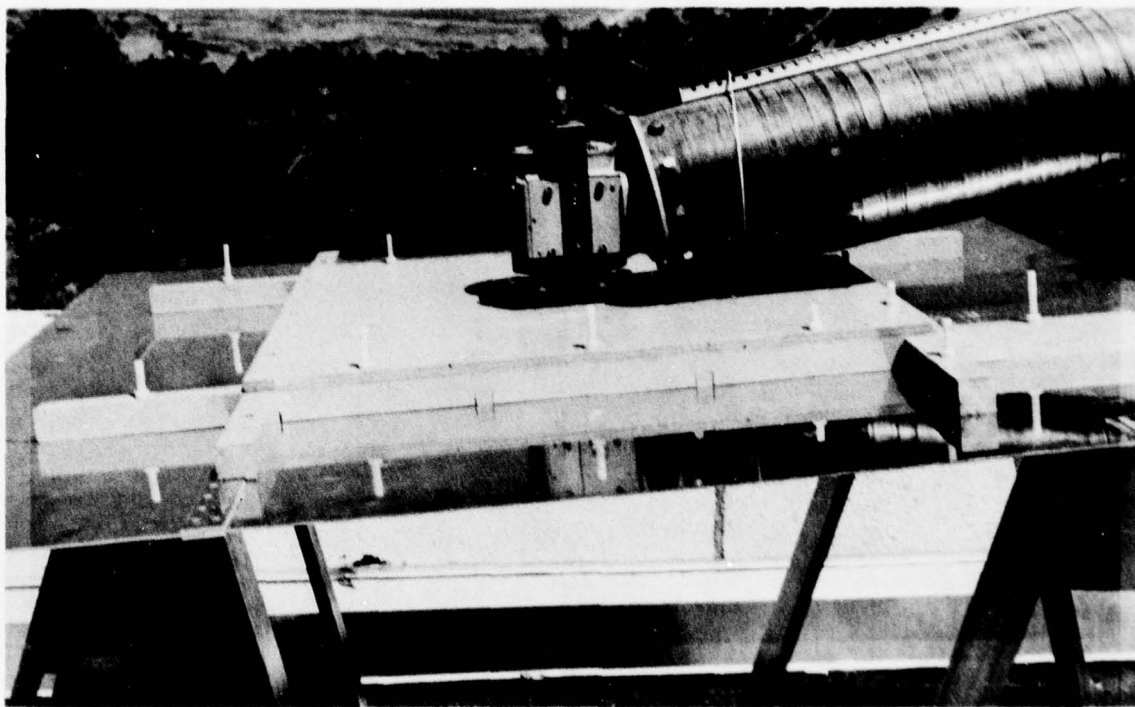


Figure 12. Ground Plane Mounting Frame

Figure 13 shows the metal ground plane mounted on the raised boom and with a dipole antenna under test. This is the view as seen from the transmitting antenna.

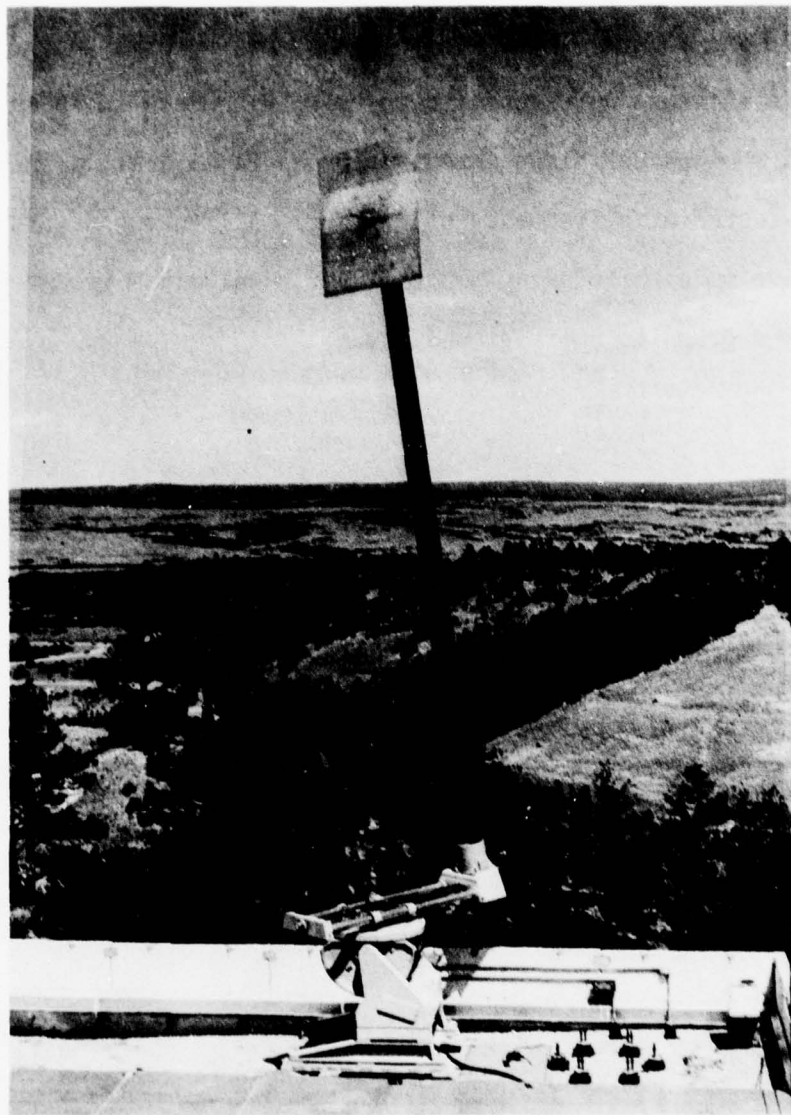


Figure 13. Antenna Boom Elevated

Antenna pattern plots were made for both monopole and dipole antennas at 370 and 837 MHz. The monopole antennas were discussed earlier. The dipole antennas were constructed by DFEE and are shown in figure 14. Figure 15 shows a UHF blade antenna from an F4 aircraft. This antenna was also tested at a frequency of 370 MHz. All antennas were tested in the receive mode while being mounted over an aluminum ground plane and then over a graphite epoxy ground plane.

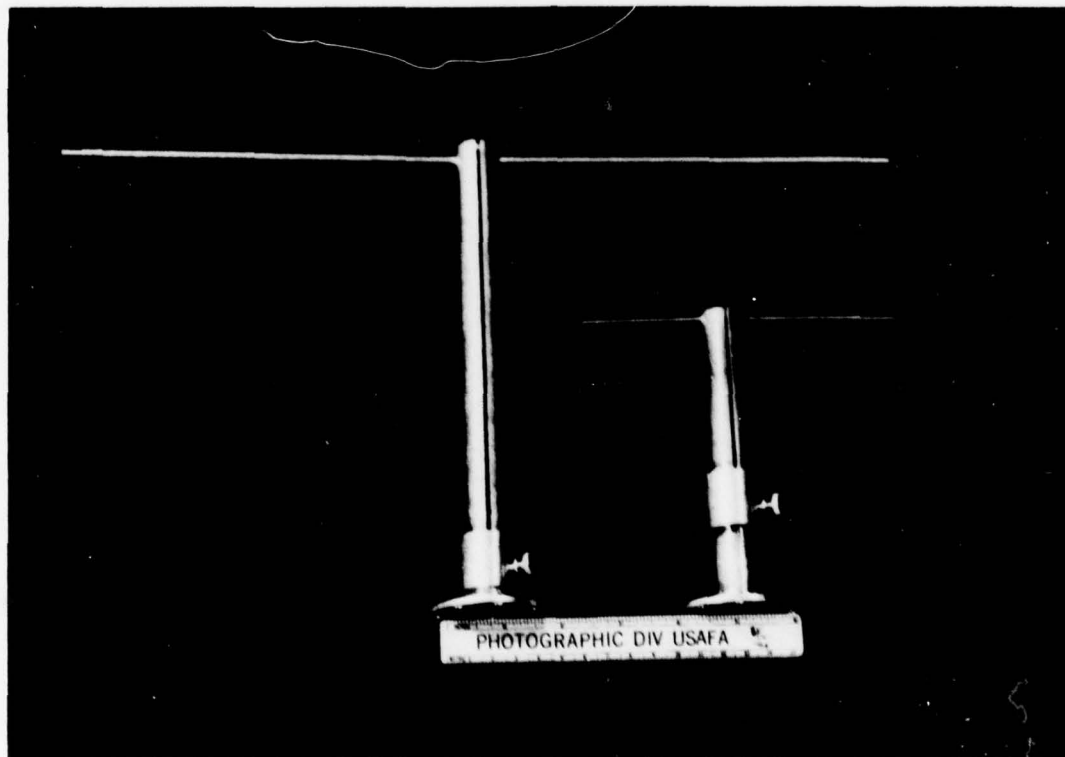


Figure 14. Dipole Antennas

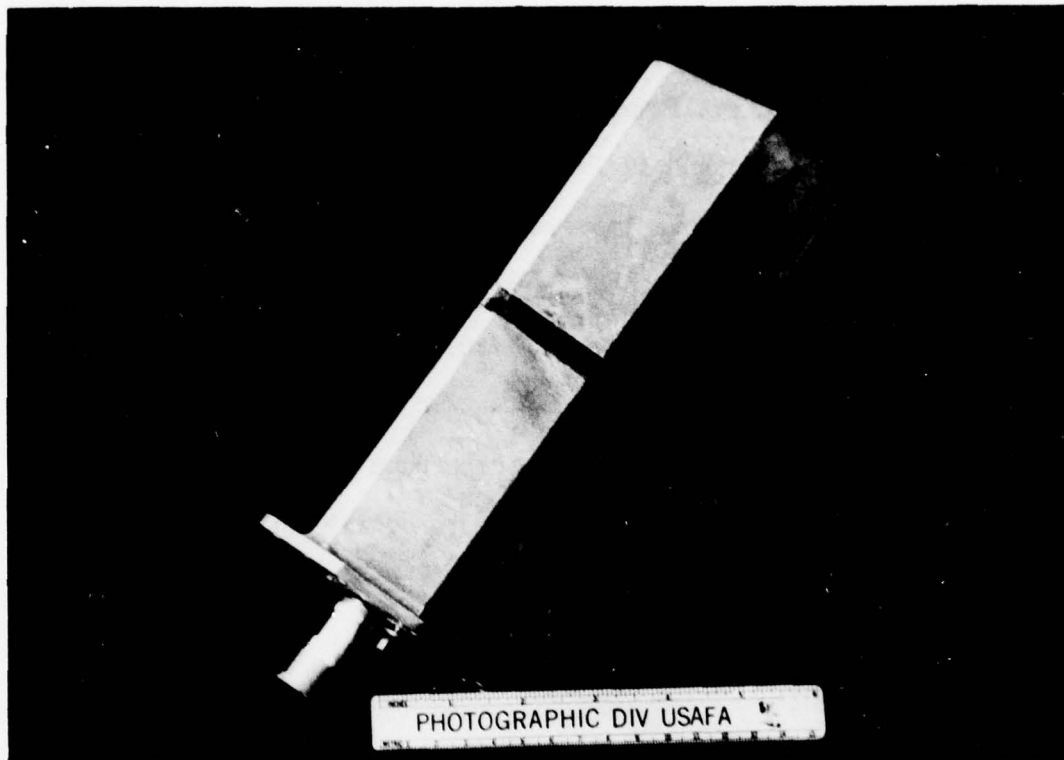


Figure 15. UHF-F4 Blade Antenna

IV. MEASUREMENT RESULTS

A. Impedance Measurements

The measured resistance and reactance of a monopole antenna is plotted in figures 16 and 17 for a frequency range of 360 to 430 MHz. These plots show the antenna impedance over both aluminum and graphite epoxy ground planes. Similar plots are shown in figures 18 and 19 for the higher frequency monopole antenna (780-900 MHz). A few "unusual" data points exist but the curves show that no differences exist that can be attributed to a difference between the ground planes. Both sets of curves indicate that these ground planes are acting very much like infinite ground planes in that the resistance is approximately 37 ohms when the antenna is at its resonance frequency (i.e. when the reactance is zero). The results of the impedance measurements indicate, therefore, that the graphite epoxy ground plane behaves the same as the aluminum ground plane at 400 and 800 MHz.

B. Antenna Pattern Measurements

Antenna patterns were measured over graphite epoxy and aluminum at 370 MHz for the monopole, dipole and UHF F4 blade antenna. In addition patterns were plotted at 837 MHz for a monopole and dipole antenna. To understand the antenna patterns which follow, it is necessary to establish a coordinate system which will allow the antenna pattern "cuts" to be clearly defined. This coordinate system is shown in figure 20 for the dipole antenna, figure 21 for the monopole and figure 22 for the UHF F4 antenna.

RESISTANCE OF MONOPOLE ANTENNA

(360 - 430 MHz)

Δ - Over aluminum ground plane

O - Over graphite epoxy ground plane

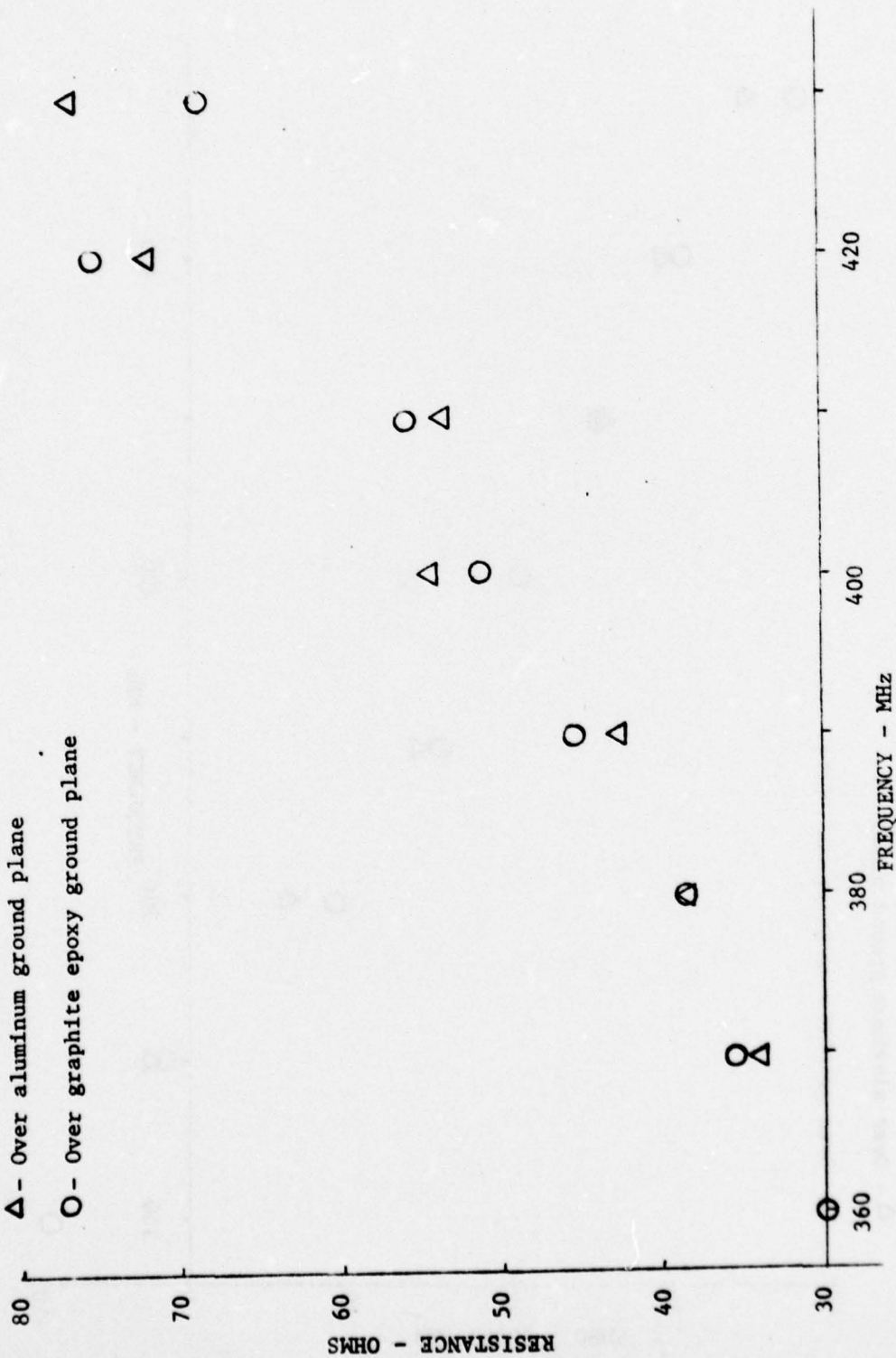


Figure 16. Resistance of Monopole Antenna at 400 MHz

REACTANCE OF MONOPOLE ANTENNA

(360 - 430 MHz)

Δ - Over aluminum ground plane

O - Over graphite epoxy ground plane

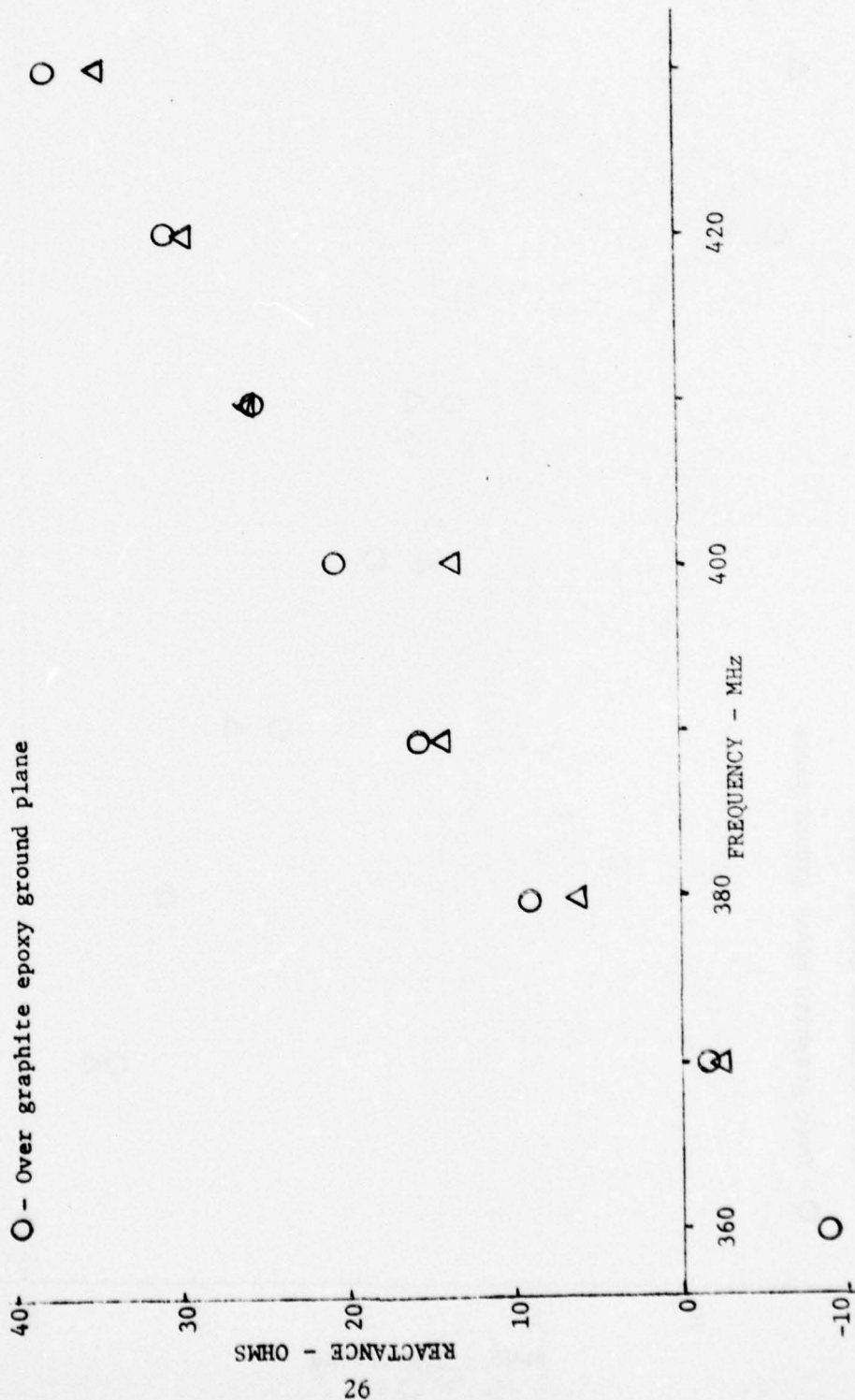


Figure 17. Reactance of Monopole Antenna at 400 MHz

RESISTANCE OF MONOPOLE ANTENNA

(780 - 900 MHz)

- △ - Over aluminum ground plane
- - Over graphite epoxy ground plane

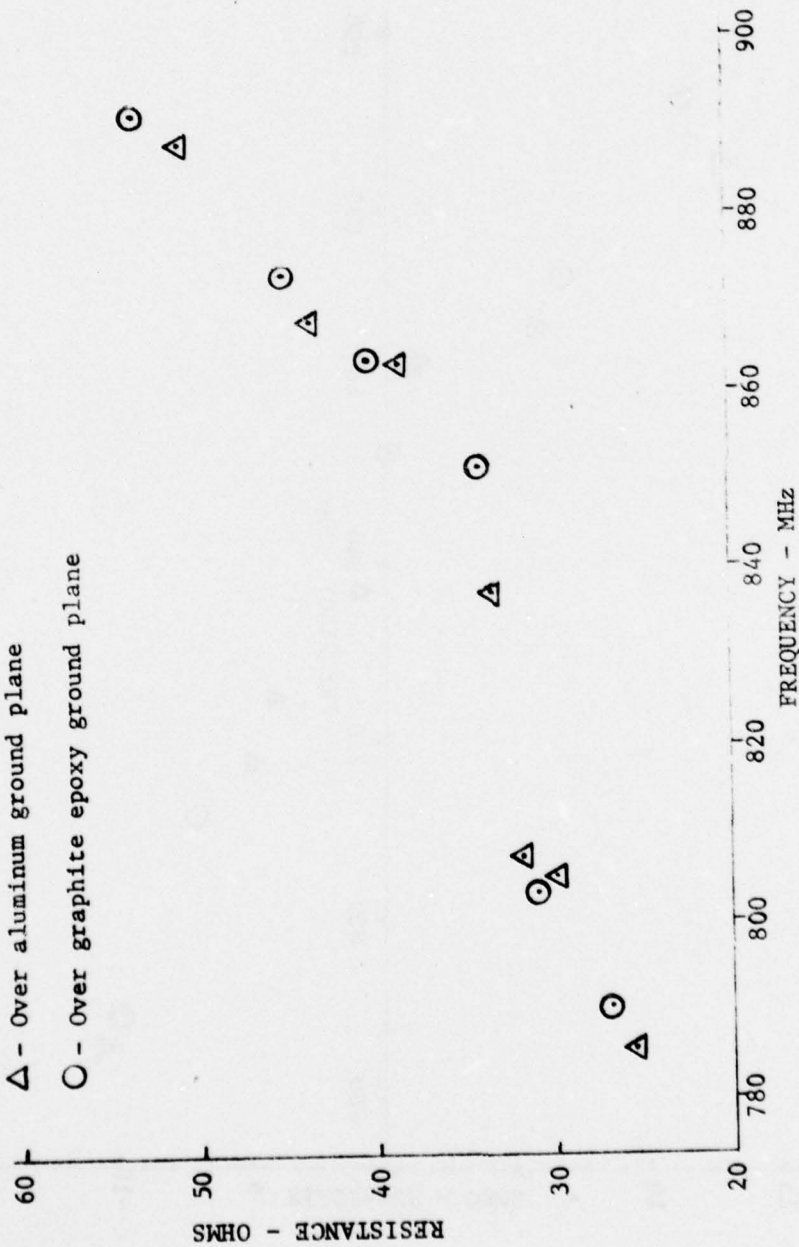


Figure 18. Resistance of Monopole Antenna at 800 MHz

REACTANCE OF MONOPOLE ANTENNA

(780 - 900 MHz)

Δ - Over aluminum ground plane

○ - Over graphite epoxy ground plane

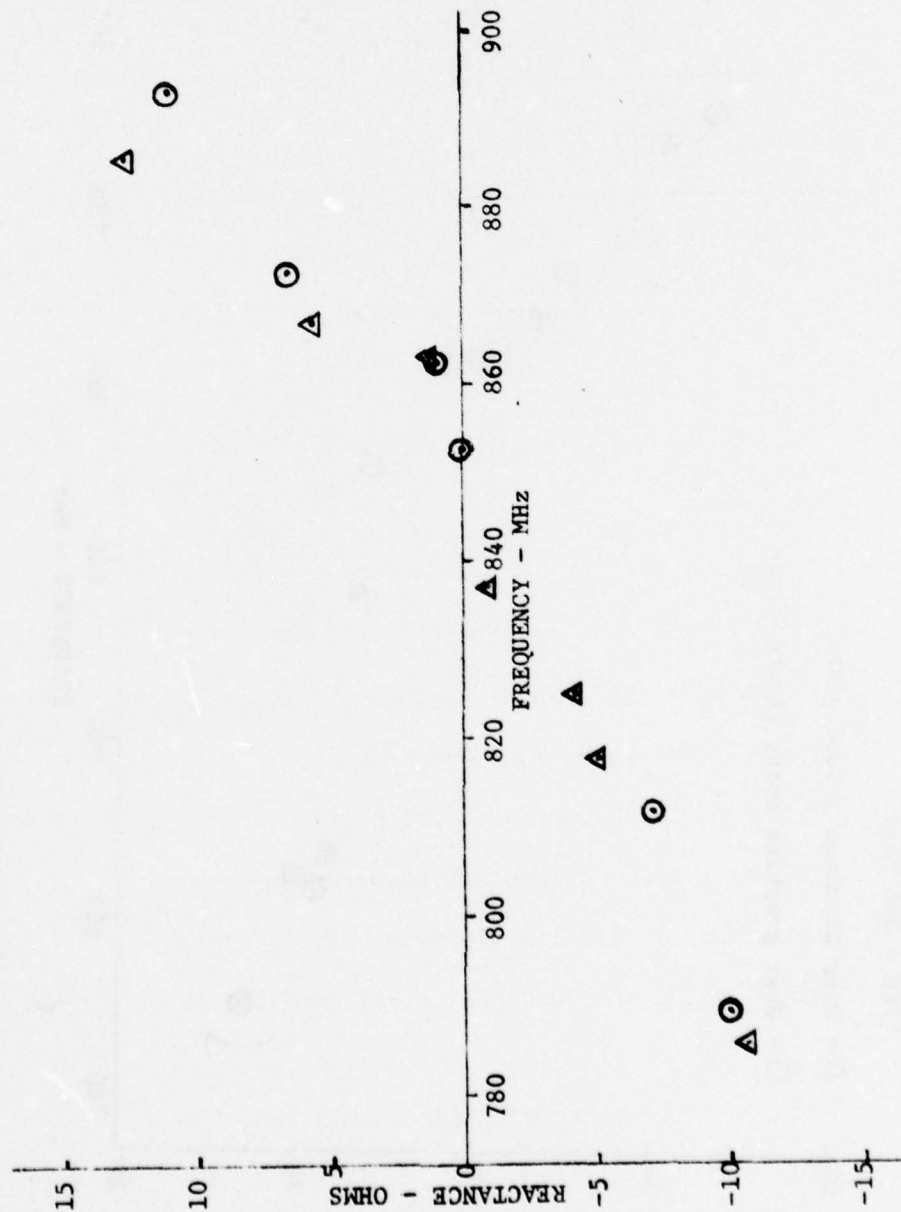


Figure 19. Reactance of Monopole Antenna at 800 MHz

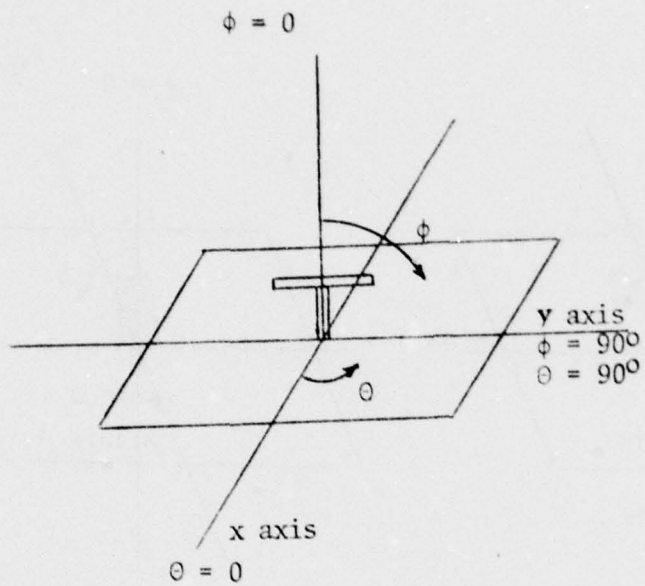


Figure 20. Dipole Coordinates

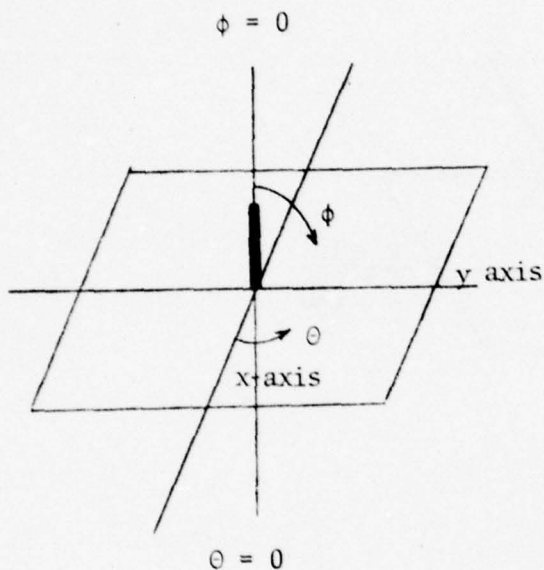


Figure 21. Monopole Coordinates

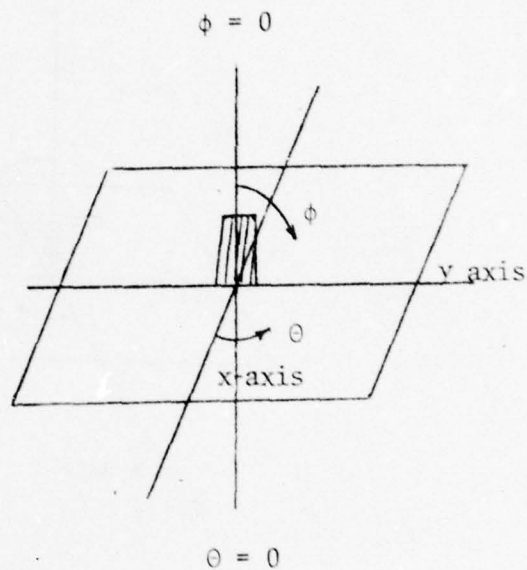


Figure 22. UHF-F4 Coordinates

Figures 23 through 28 show the various antenna patterns made with a dipole antenna at 370 MHz. For each set of pictures, the pattern with graphite epoxy is shown first followed by the equivalent pattern with aluminum. In each case the antenna pattern was made with the E plane of the receive antenna aligned with the E field of the transmitter antenna. In each pair of patterns it is seen that the shape of the pattern is the same.

Figures 29 through 32 show additional antenna patterns at 370 MHz but using a monopole antenna. Plots for the UHF-4 antenna are shown in figures 33 and 34. The plots for the monopole and F4 antennas show a

change of signal power from the set of graphite epoxy plots to the aluminum ground plane plots. This is because all of the aluminum plots were run together and then all of the graphite epoxy plots were done. Transmitted power dropped considerably before the second set of plots could be obtained. While this makes the plots more difficult to interpret, close examination shows that the shape has remained the same even in those plots where the decreased radiated power has caused the magnitude to decrease.

Figures 35 through 44 are the patterns for the dipole and monopole antennas at 837 MHz. Again, transmitted power dropped before the composite material patterns were run but the shape of the patterns can be seen to be the same for both ground planes.

While these antenna pattern plots provide additional evidence that the aluminum and graphite epoxy ground planes behave the same at the frequencies studied, their usefulness is limited for two reasons. First is the fact that the signal power was constant for both sets of measurements in only a few of the cases measured. In most cases, therefore, it was not possible to compare signal strength and only the shape of the pattern could be compared. Second was the conclusion reported in the theory section that a difference between ground planes would be perceived more as a change in the antenna patterns magnitude than in its shape.

$\Theta = 90^\circ$ Plane

10 dB per
major division

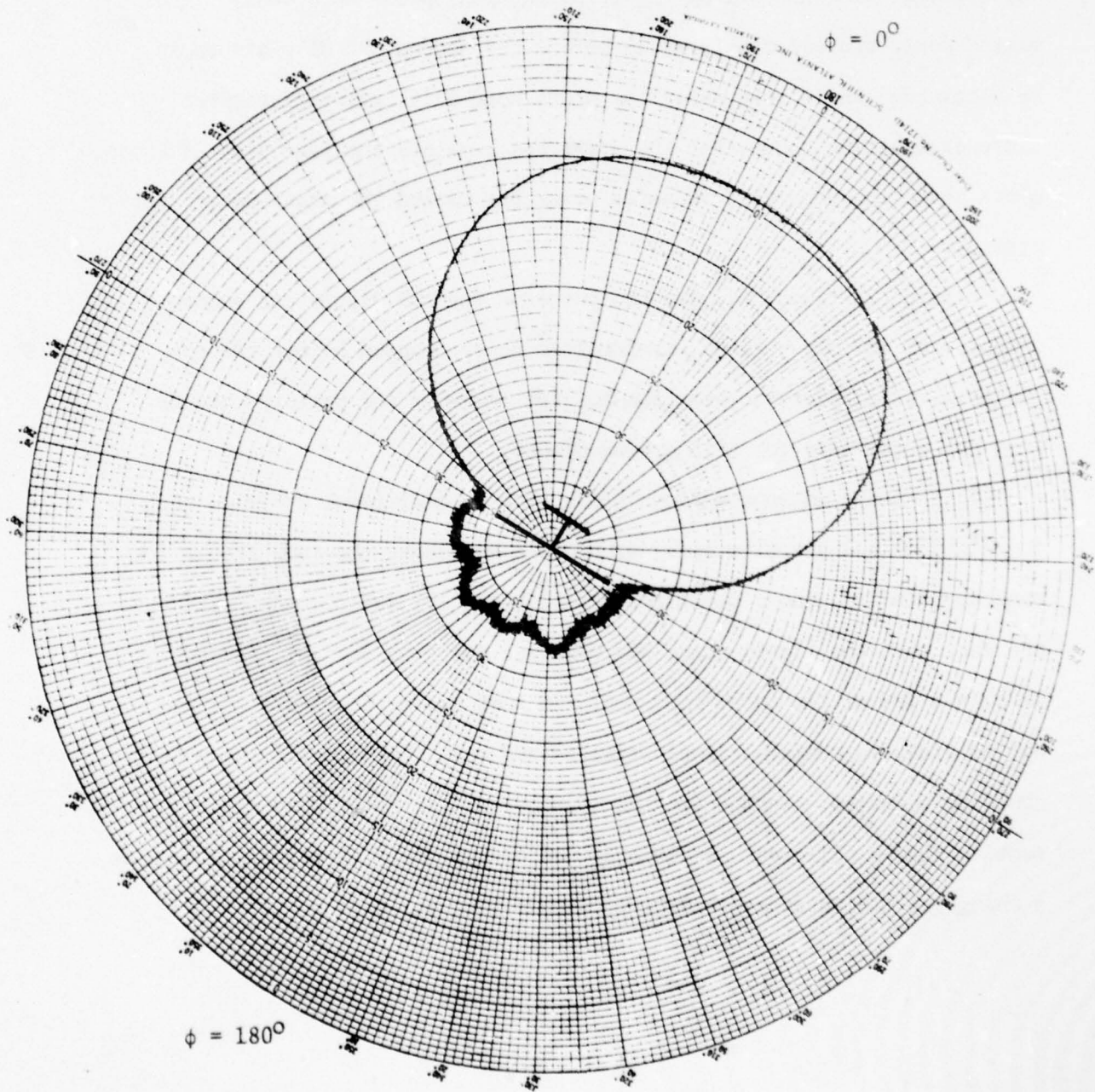


Figure 23. Dipole - Graphite Epoxy - 370 MHz

$\theta = 90^\circ$ Plane

$\phi = 0^\circ$

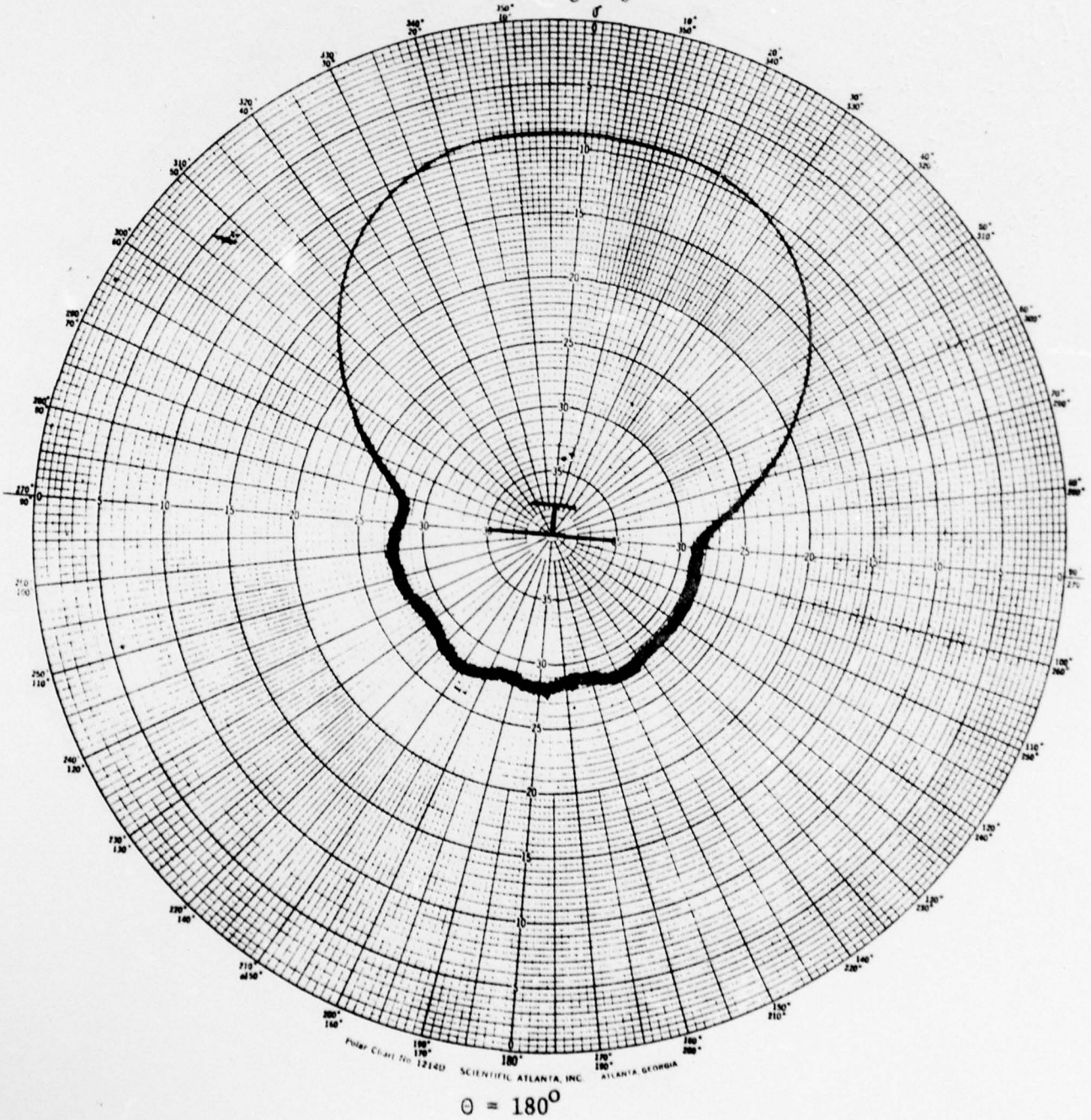


Figure 24. Dipole - Metal - 370 MHz

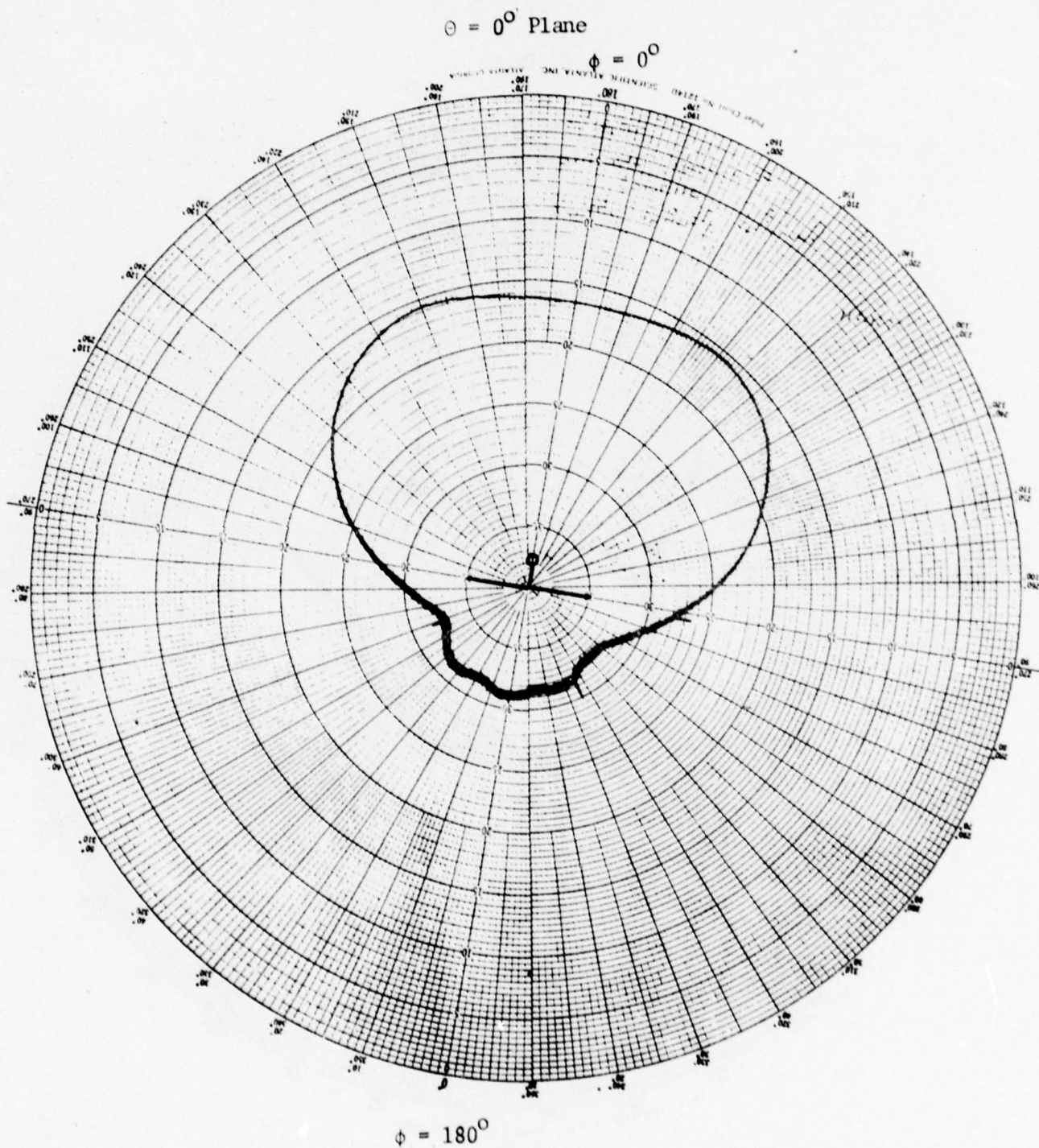


Figure 25. Dipole - Graphite Epoxy - 370 MHz

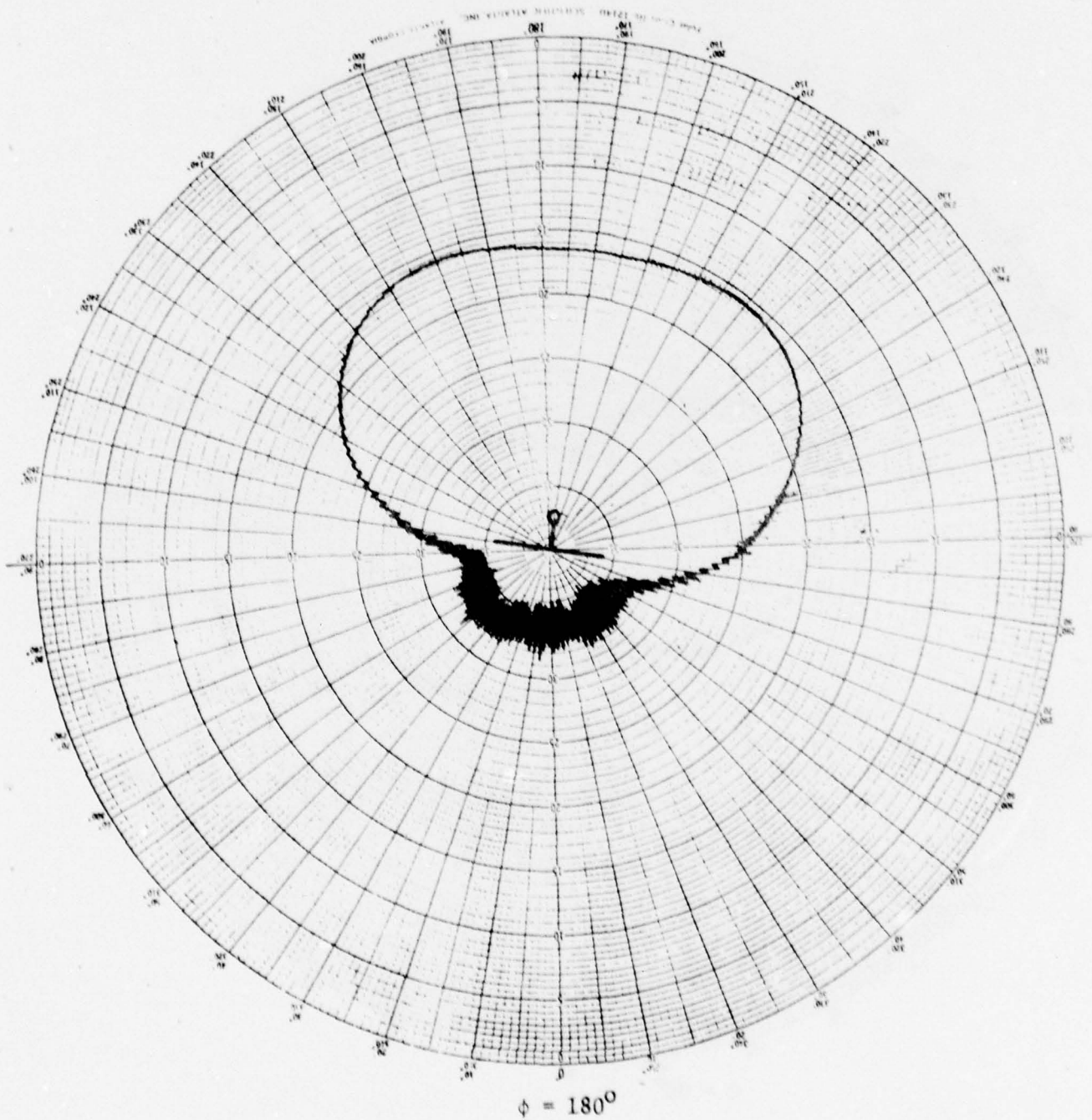
$$\Theta = 0^\circ \text{ Plane}$$
$$\Phi = 0^0$$


Figure 26. Dipole - Metal - 370 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

$\theta = 270^\circ$

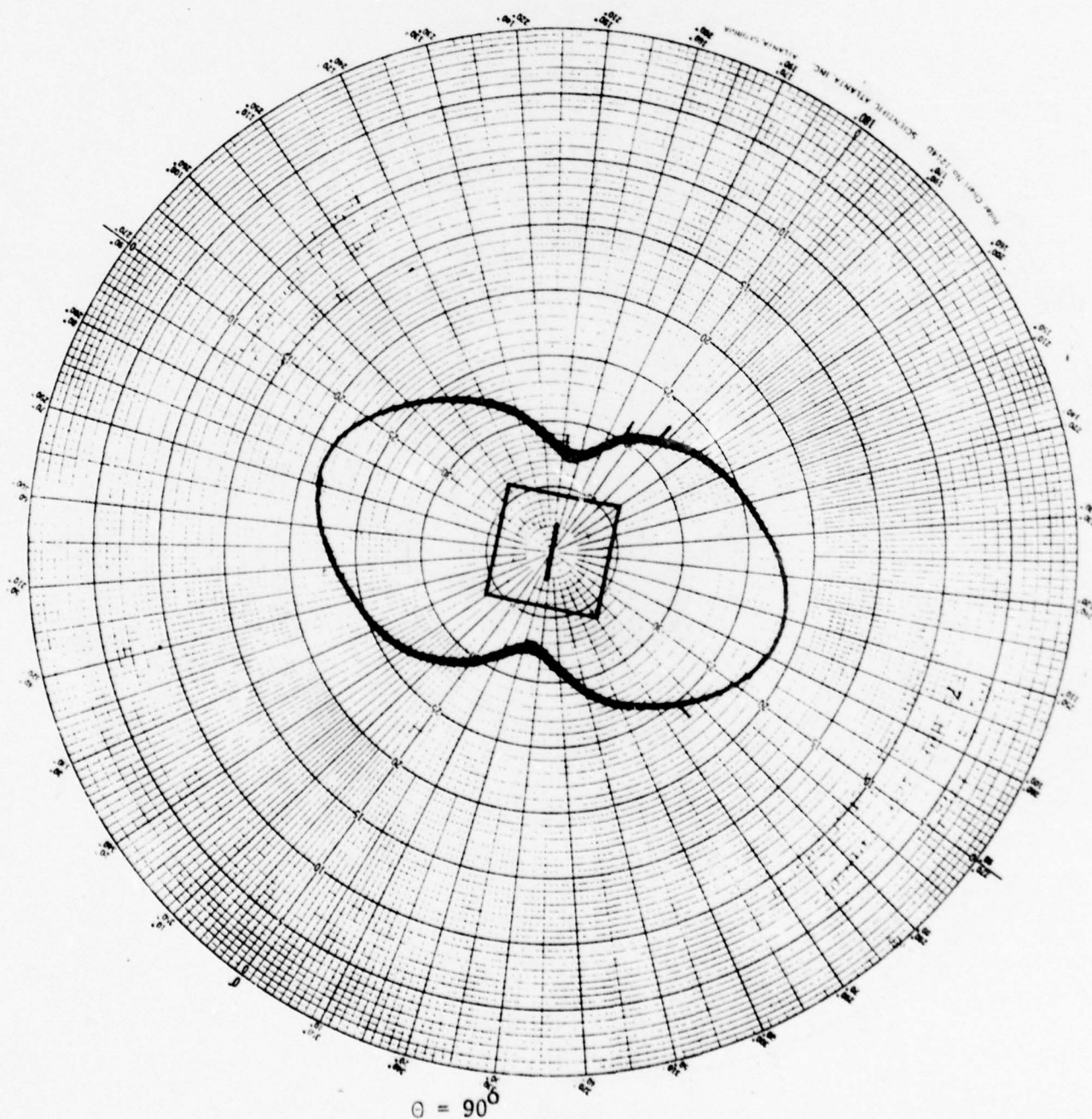


Figure 27. Dipole - Graphite Epoxy - 370 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

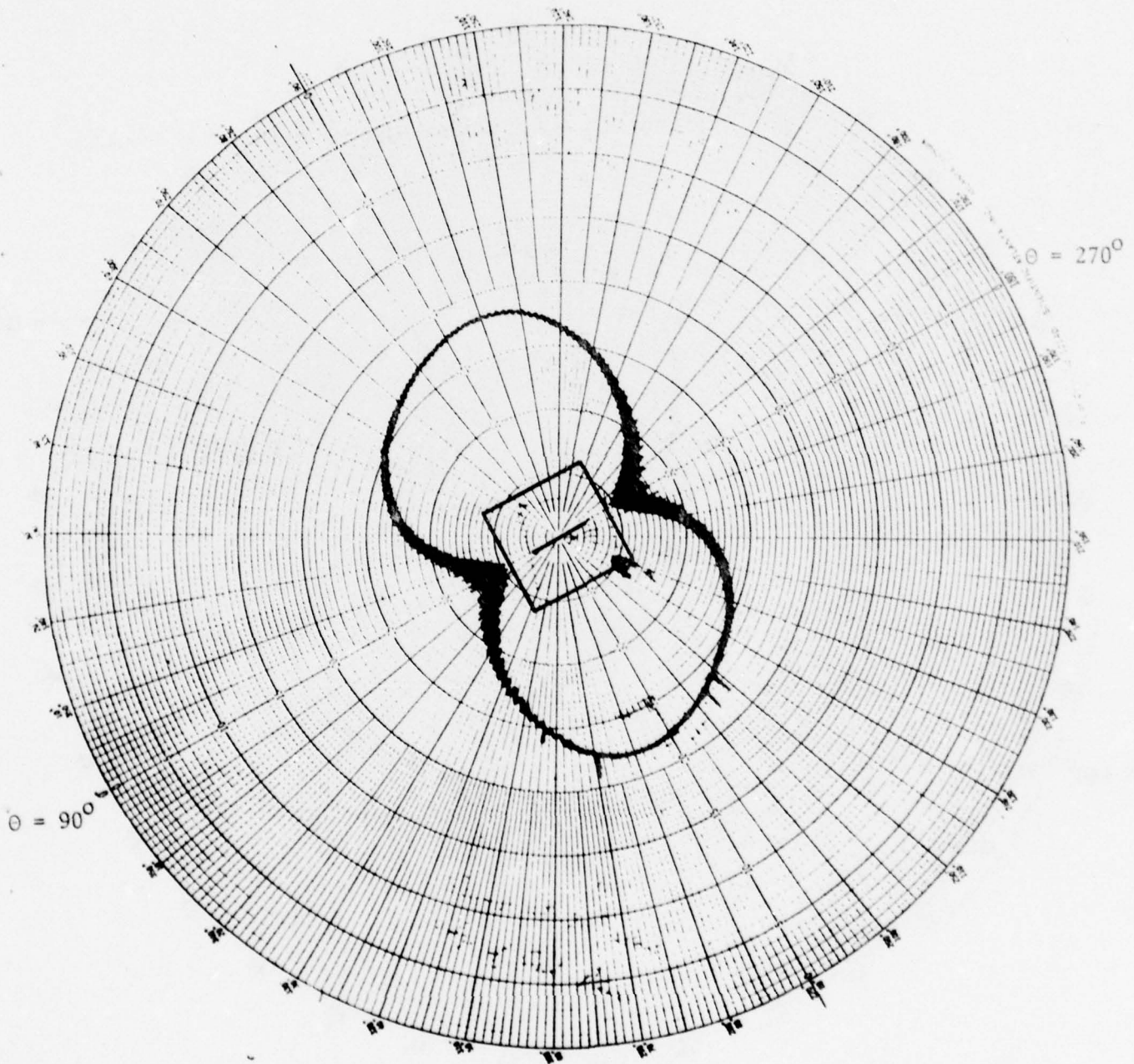


Figure 28. Dipole - Metal - 370 MHz

$\theta = 0^\circ$ Plane

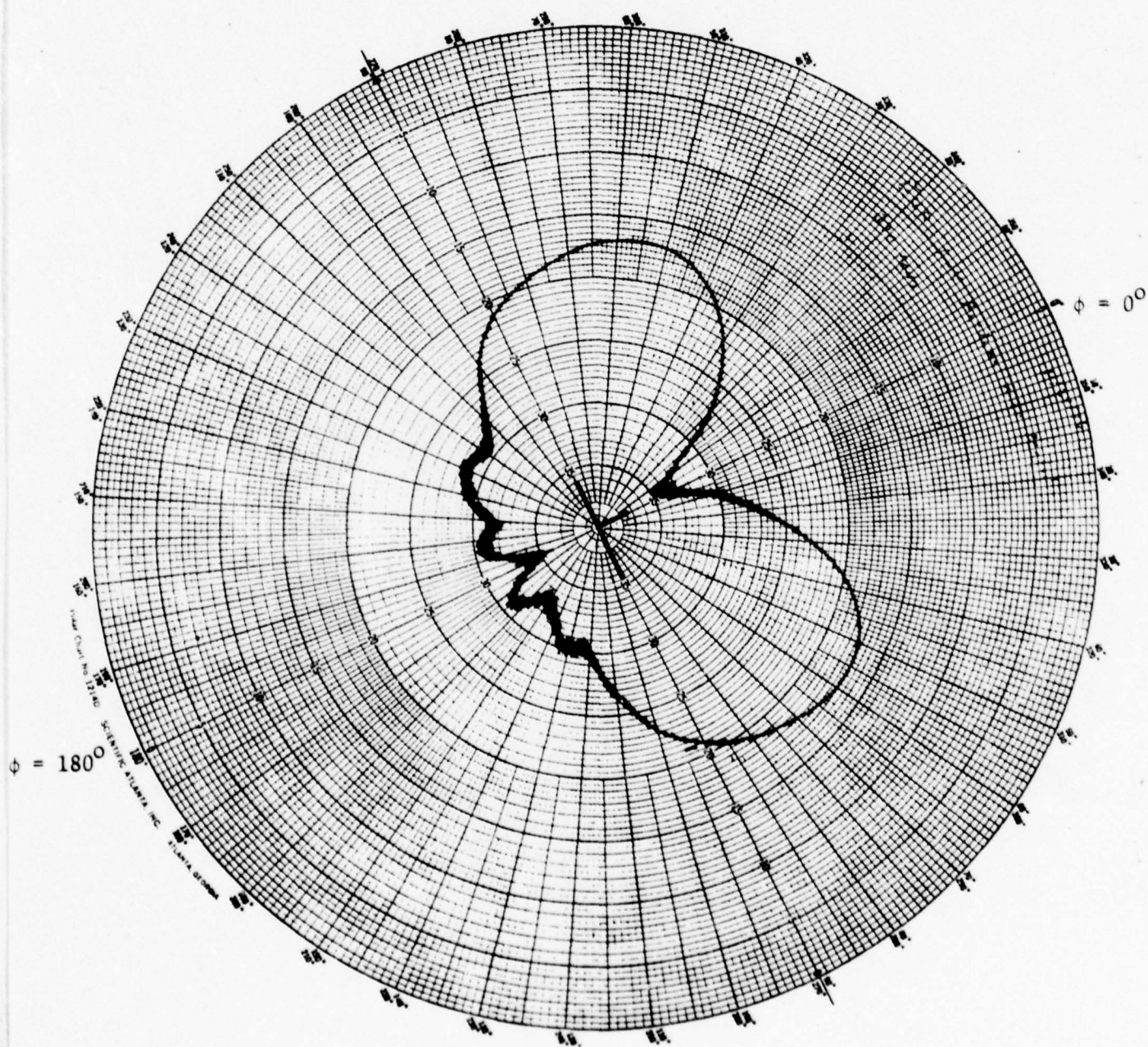


Figure 29. Monopole - Graphite Epoxy - 370 MHz

$\theta = 0^\circ$ Plane

$\phi = 0^\circ$

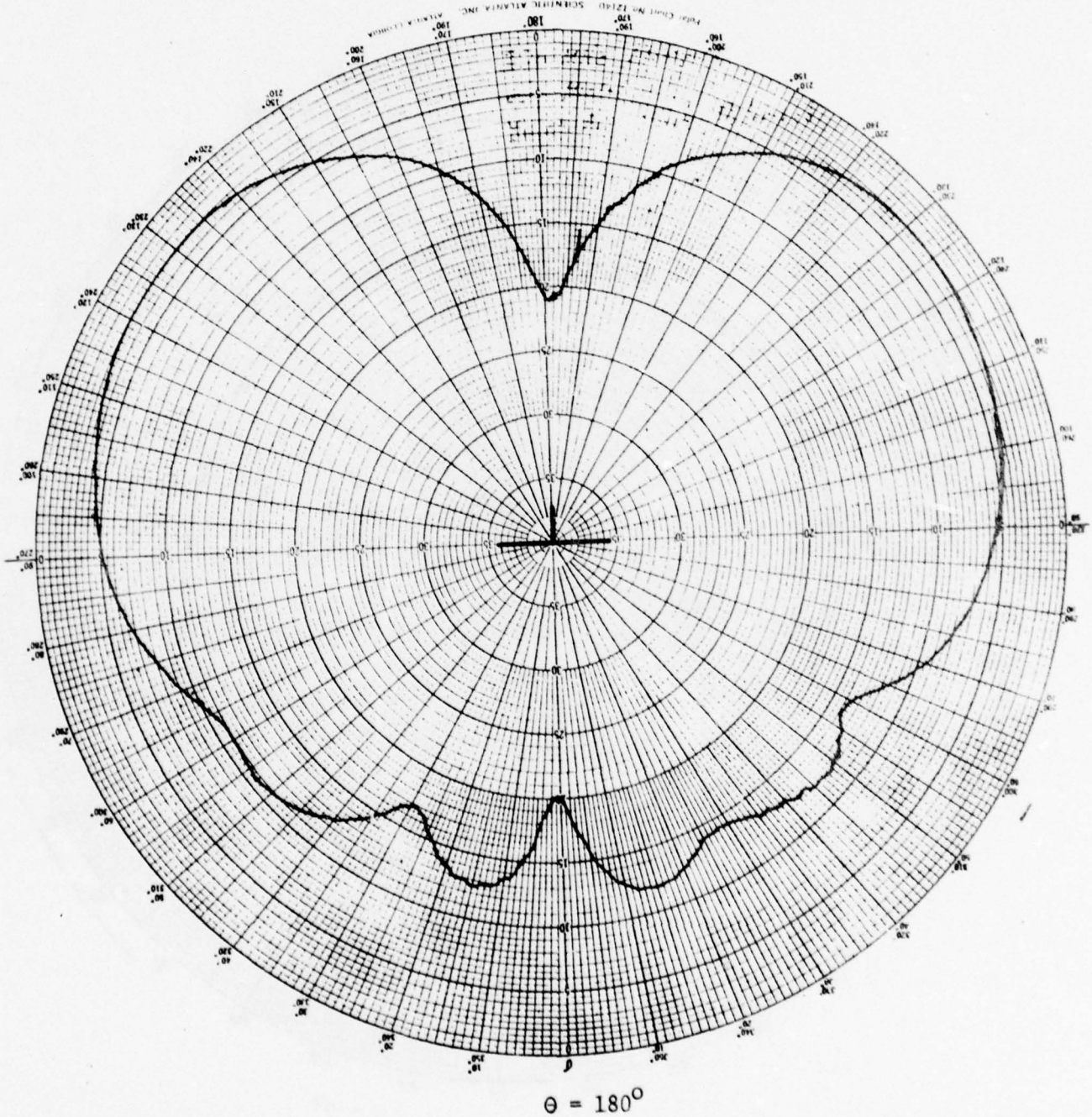


Figure 30. Monopole - Metal - 370 MHz



•

$\phi = 70^\circ$ Plane

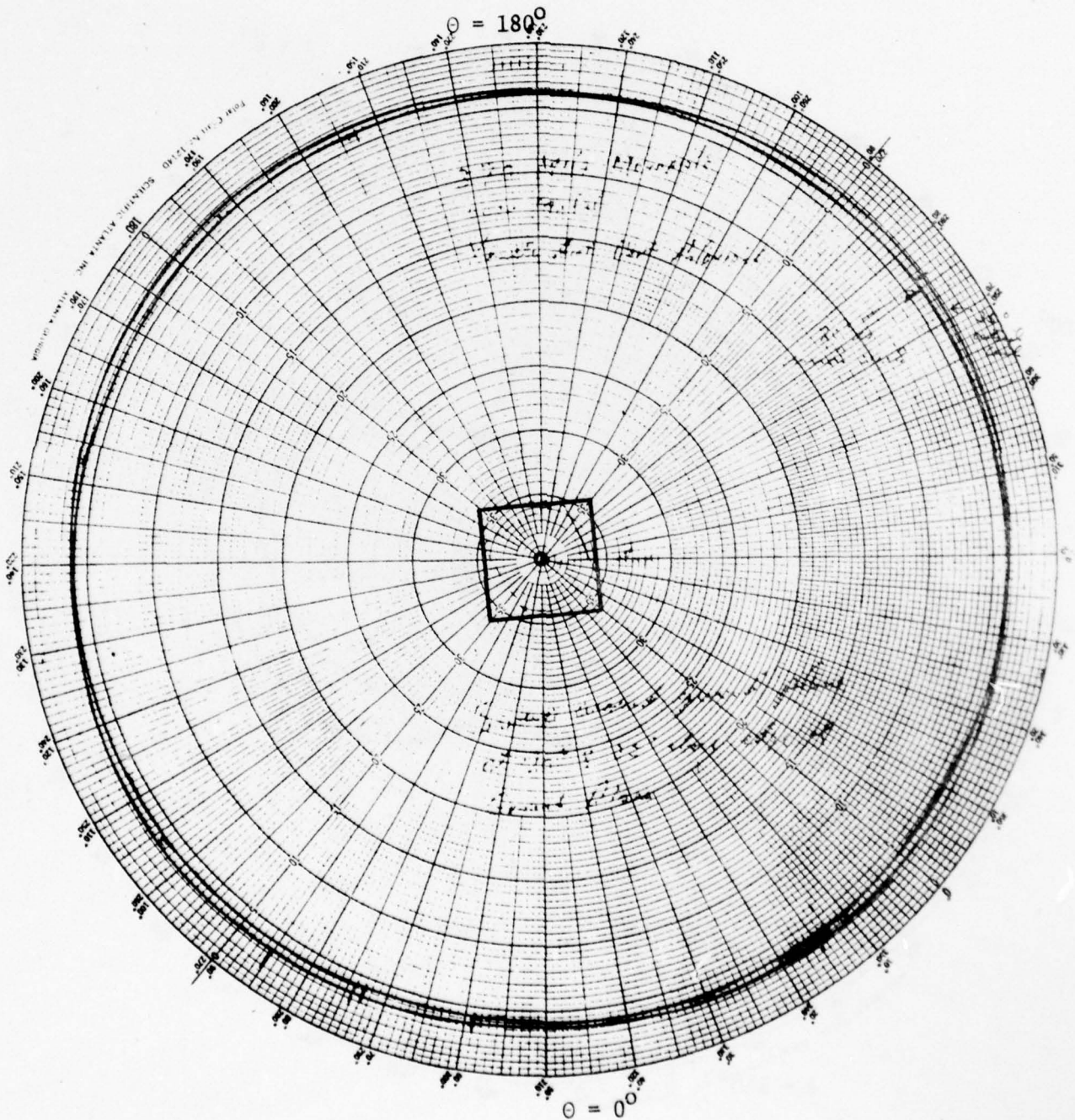


Figure 32. Monopole - Metal - 370 MHz

$\theta = 0^\circ$ Plane

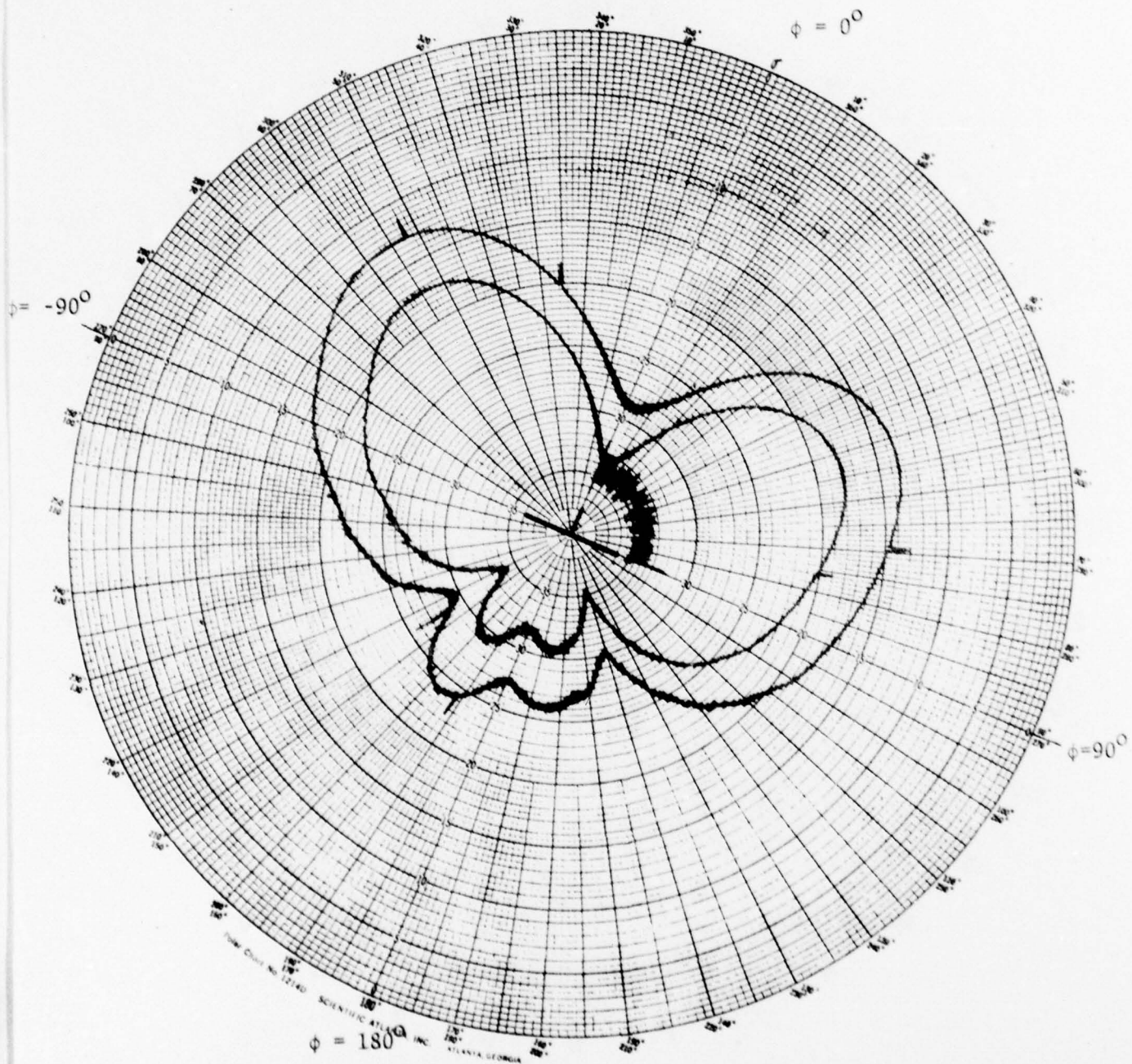


Figure 33. UHF/F4 Antenna - Graphite Epoxy - 370 MHz

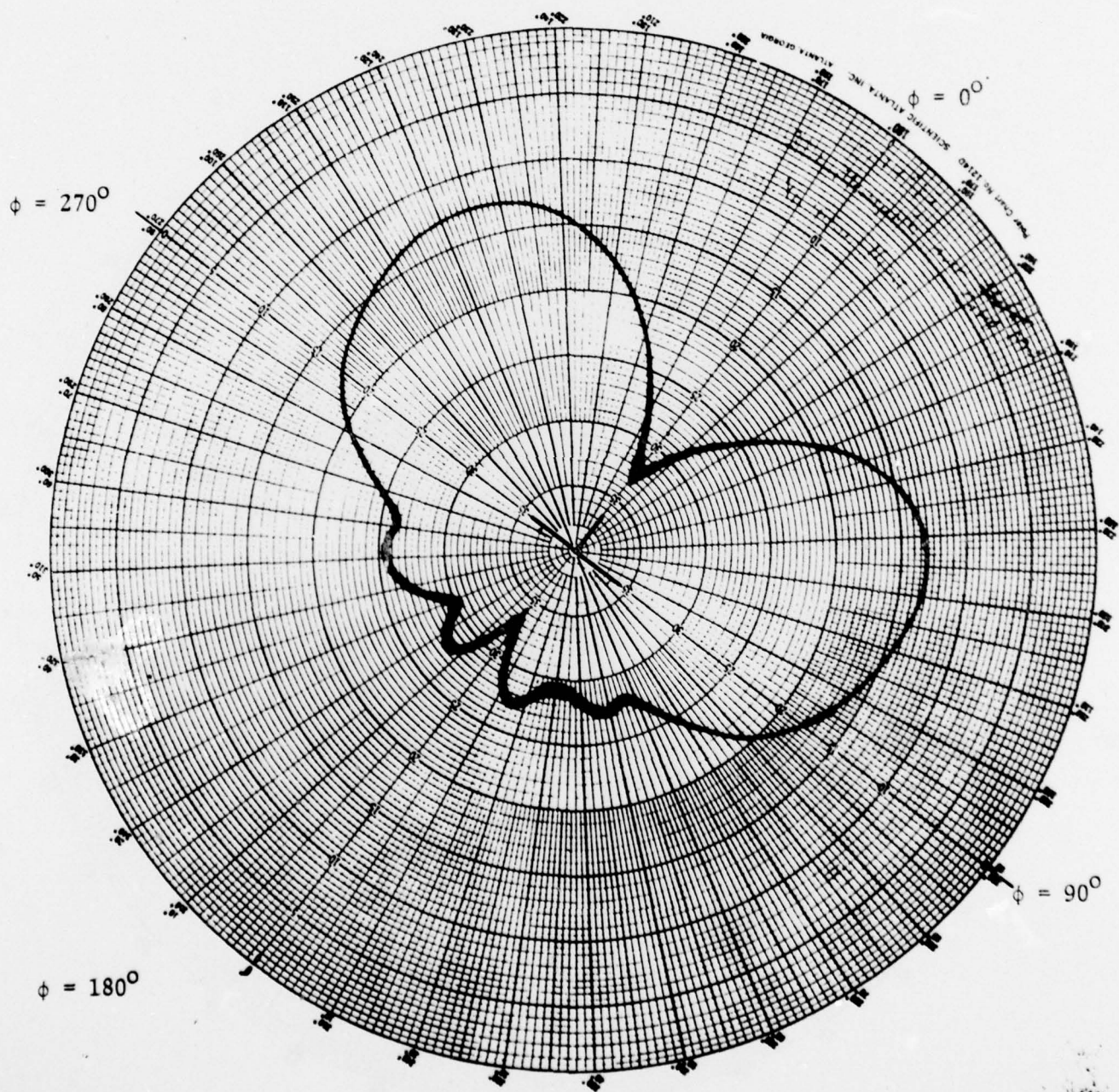
$\Theta = 0^\circ$ Plane

Figure 34. UHF/F4 Antenna - Metal - 370 MHz

$\Theta = 90^\circ$ Plane

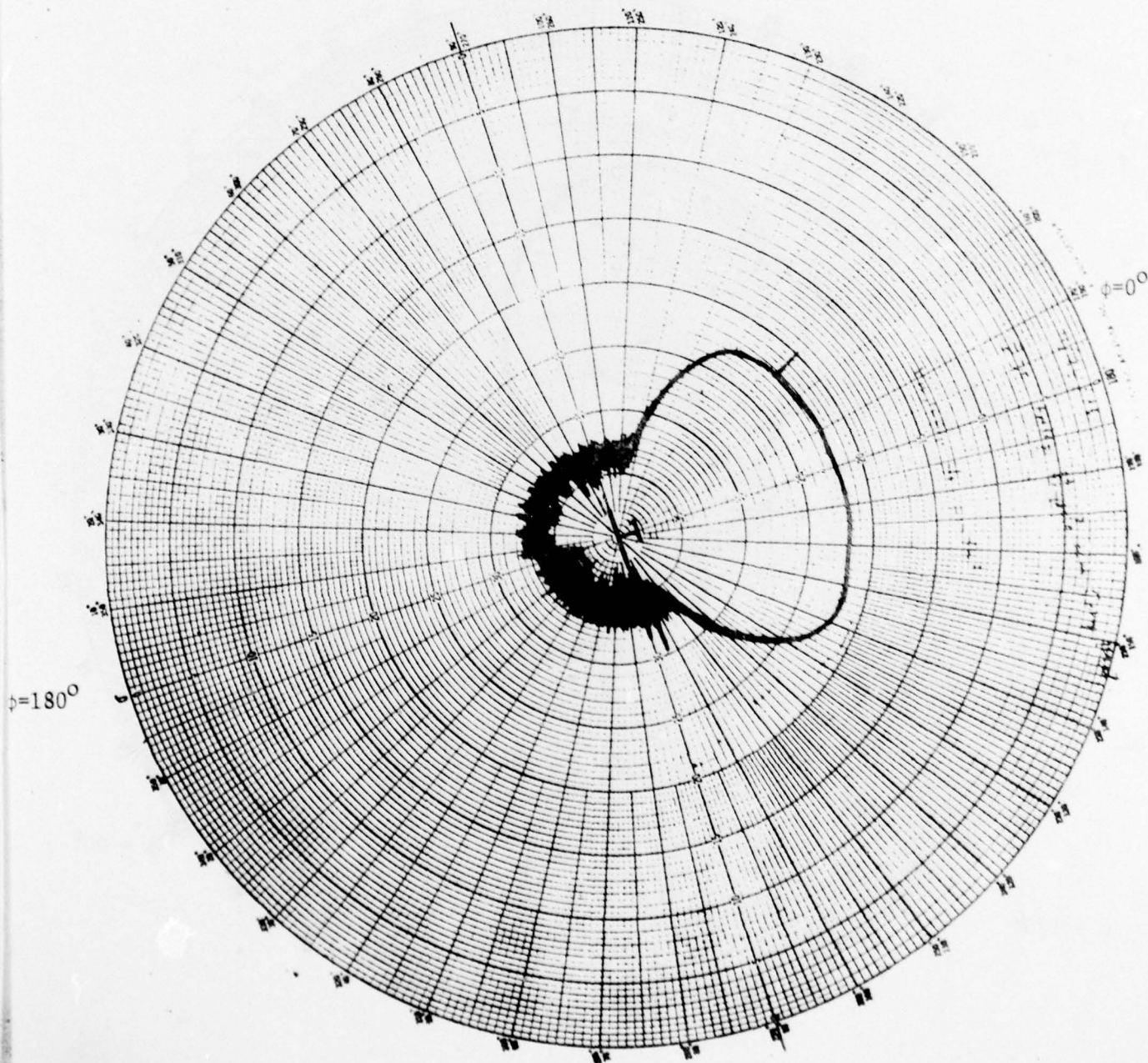


Figure 35. Dipole - Graphite Epoxy - 837 MHz

$\Theta = 90^\circ$ Plane

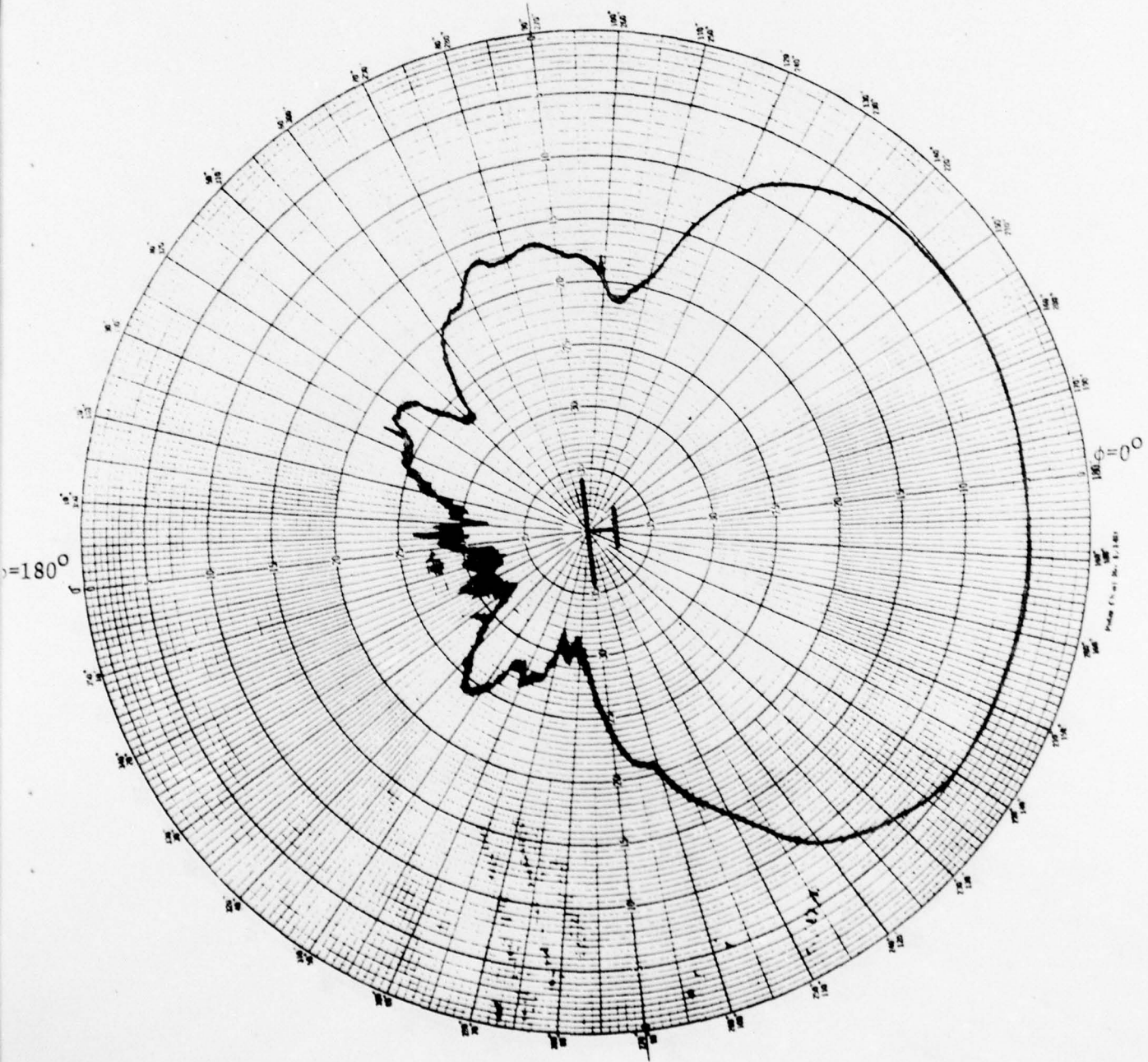


Figure 36. Dipole - Metal - 837 MHz

$\Theta = 0^\circ$ Plane

$\phi = 0^\circ$

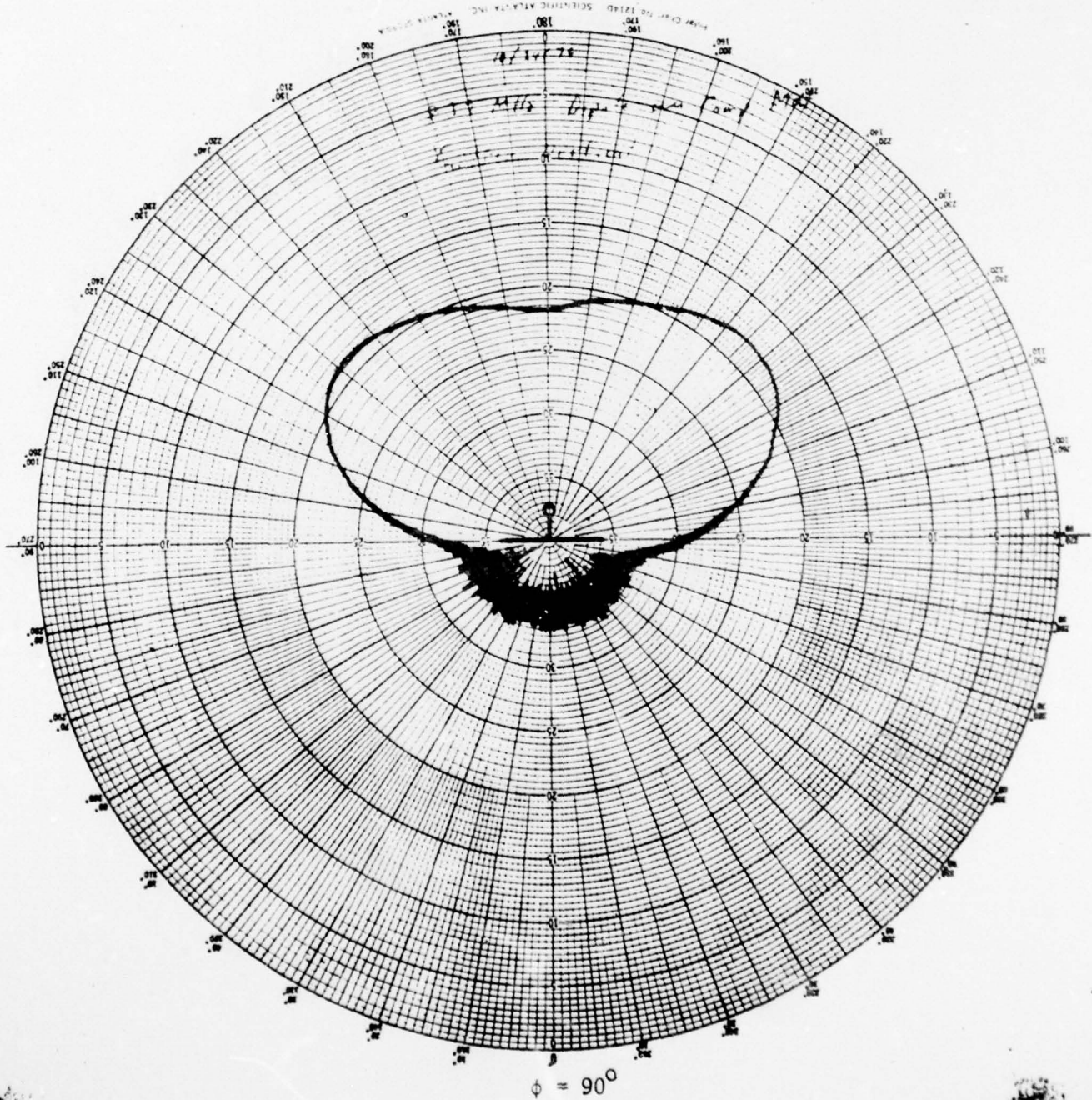


Figure 37. Dipole - Graphite Epoxy - 837 MHz

$\theta = 0^\circ$ Plane

$\phi = 90^\circ$

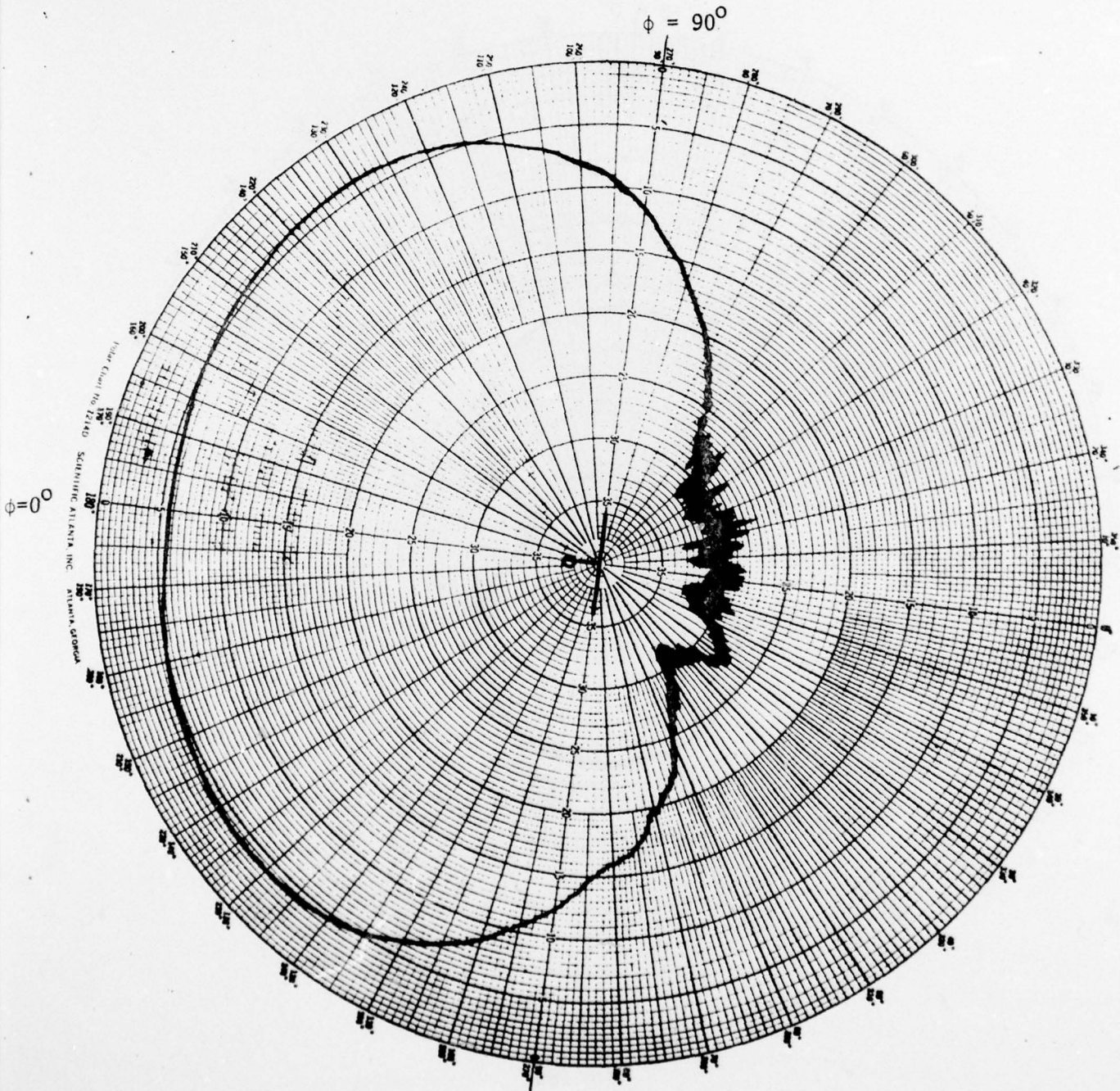


Figure 38. Dipole - Metal - 837 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

$\theta = 0^\circ$

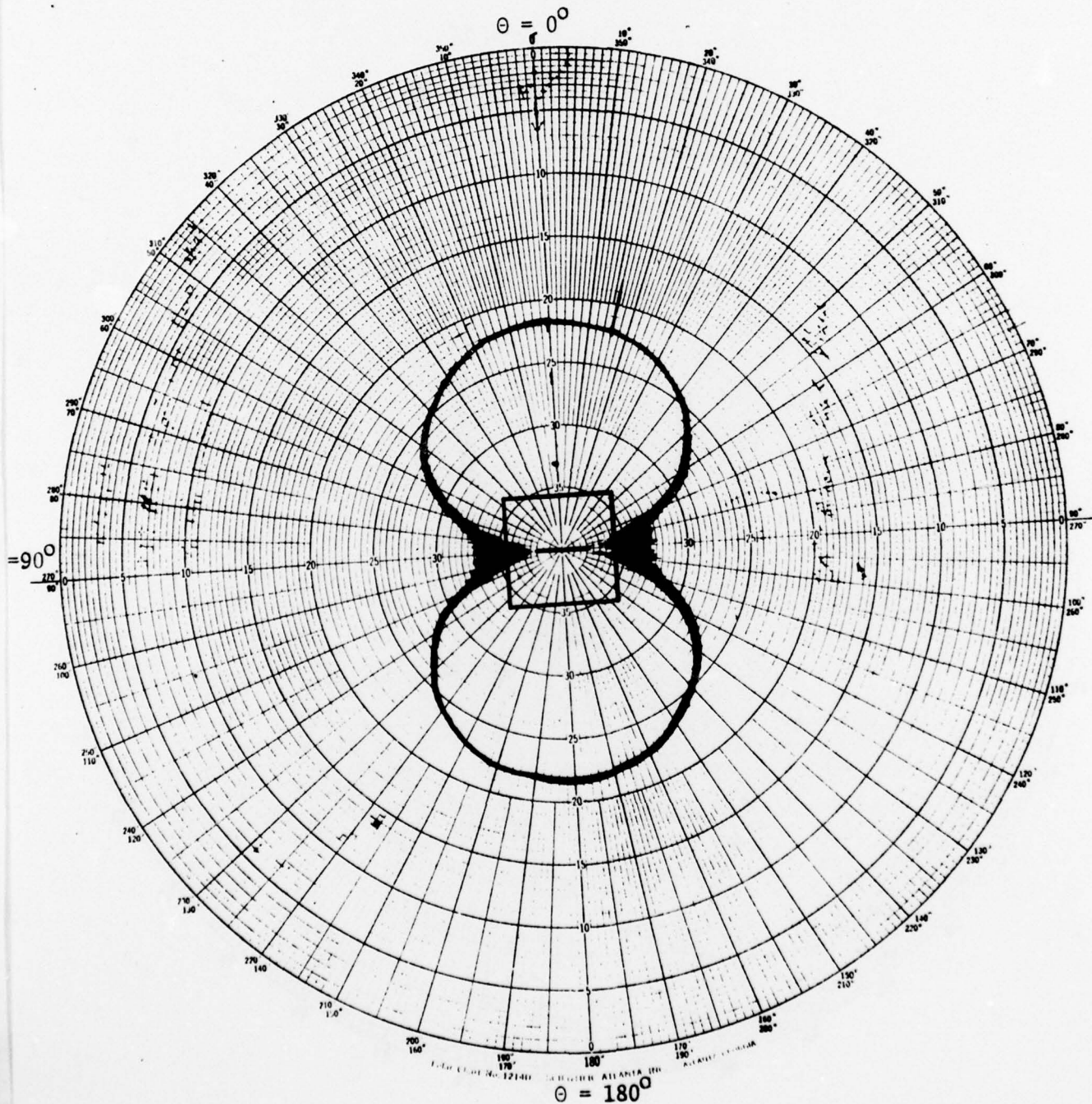


Figure 39. Dipole - Graphite - 837 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

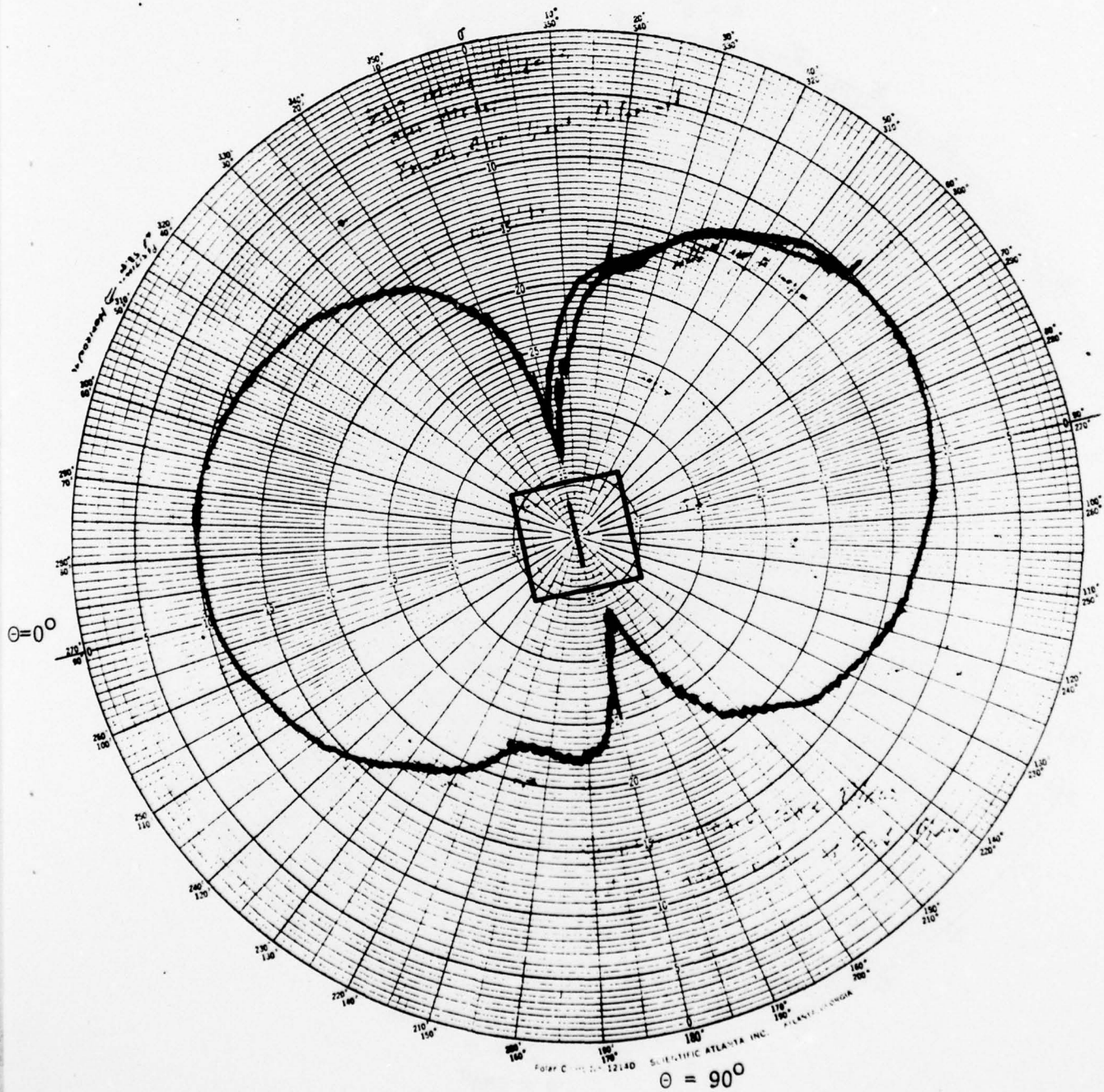


Figure 40. Dipole - Metal - 837 MHz

$\Theta = 0$ Plane

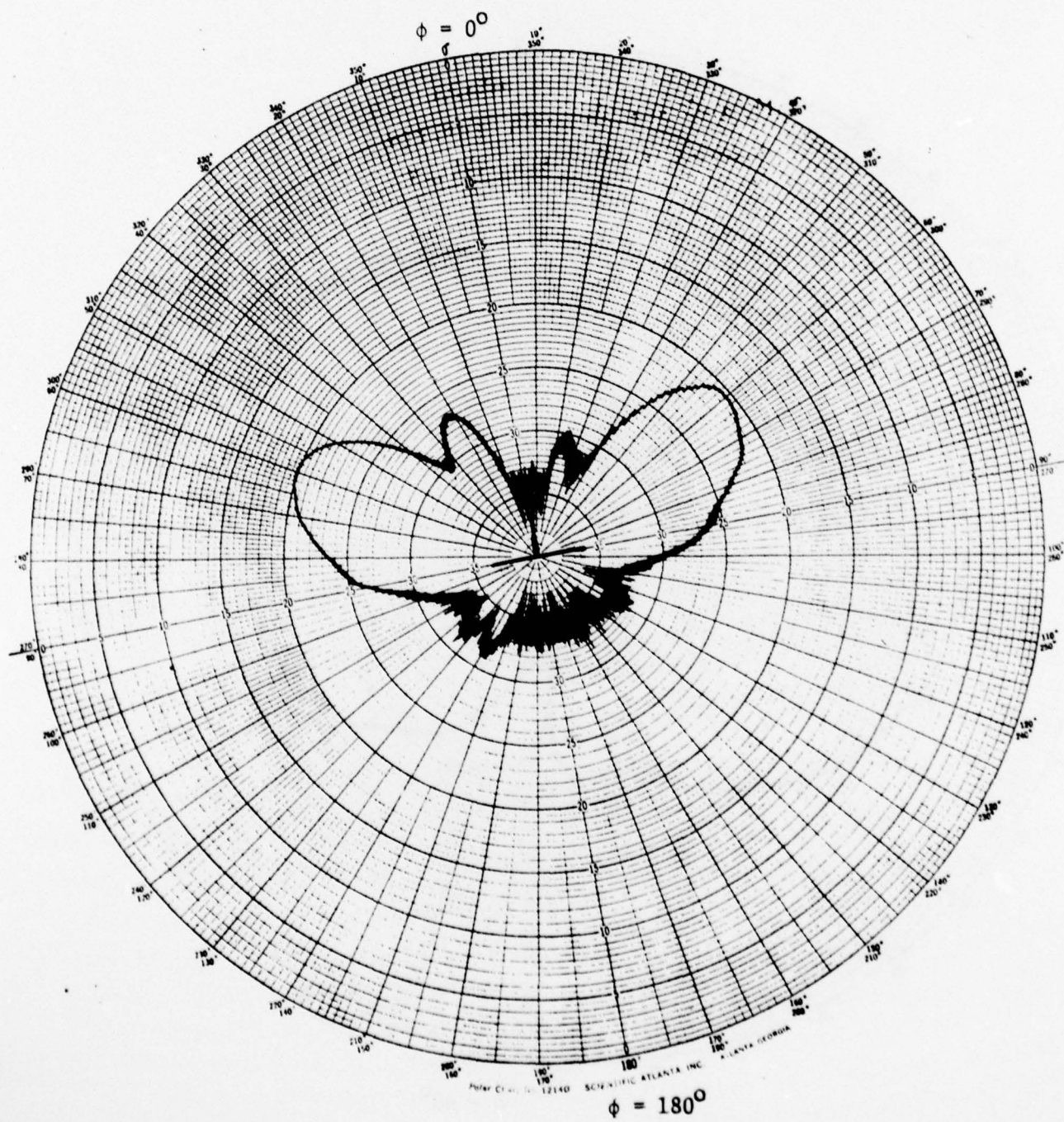


Figure 41. Monopole - Graphite Epoxy - 837 MHz

$\Theta = 0$ Plane

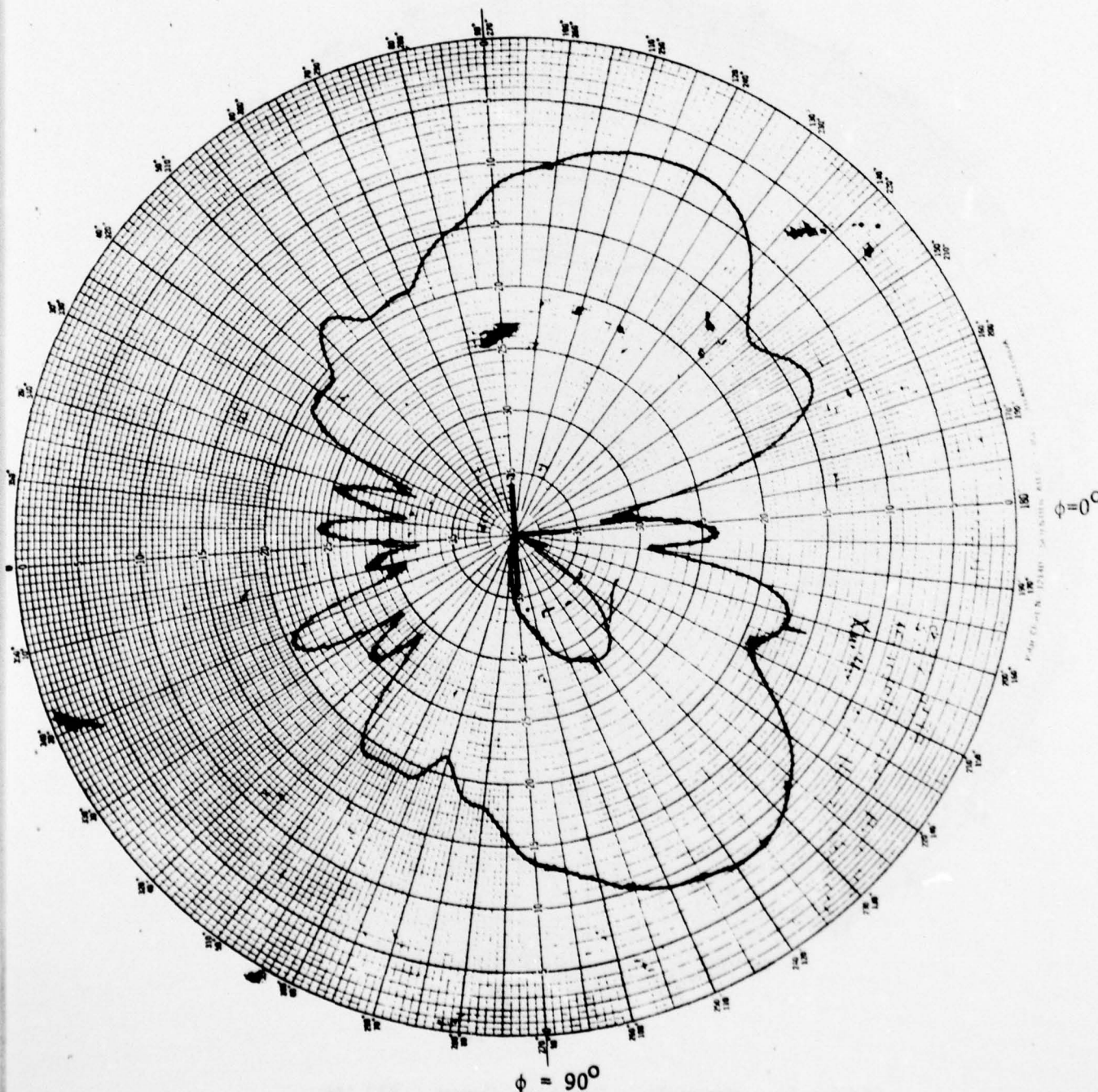


Figure 42. Monopole - Metal - 837 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

$\theta = 0^\circ$

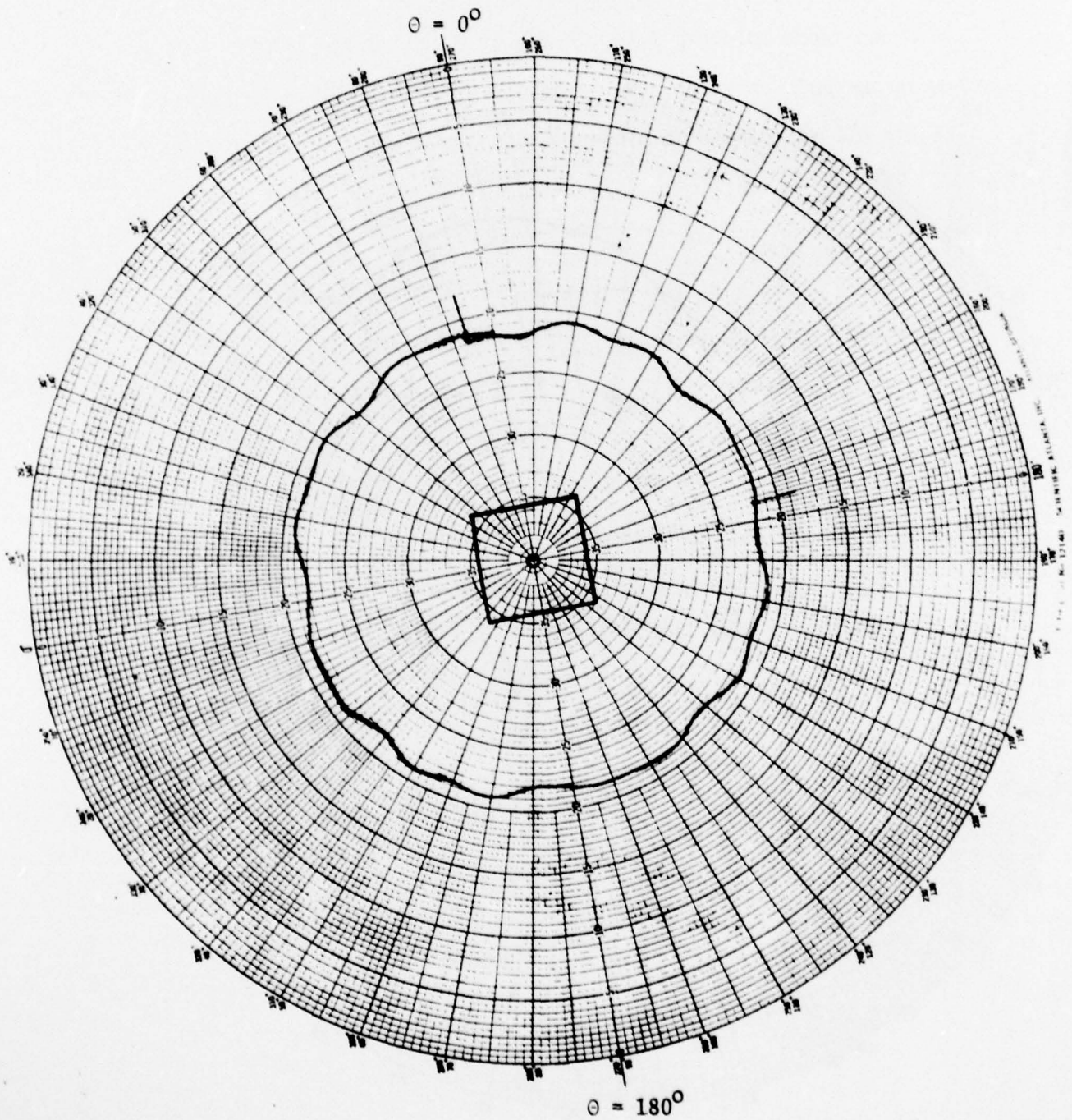


Figure 43. Monopole - Graphite Epoxy - 837 MHz

Conical Pattern

$\phi = 70^\circ$ Plane

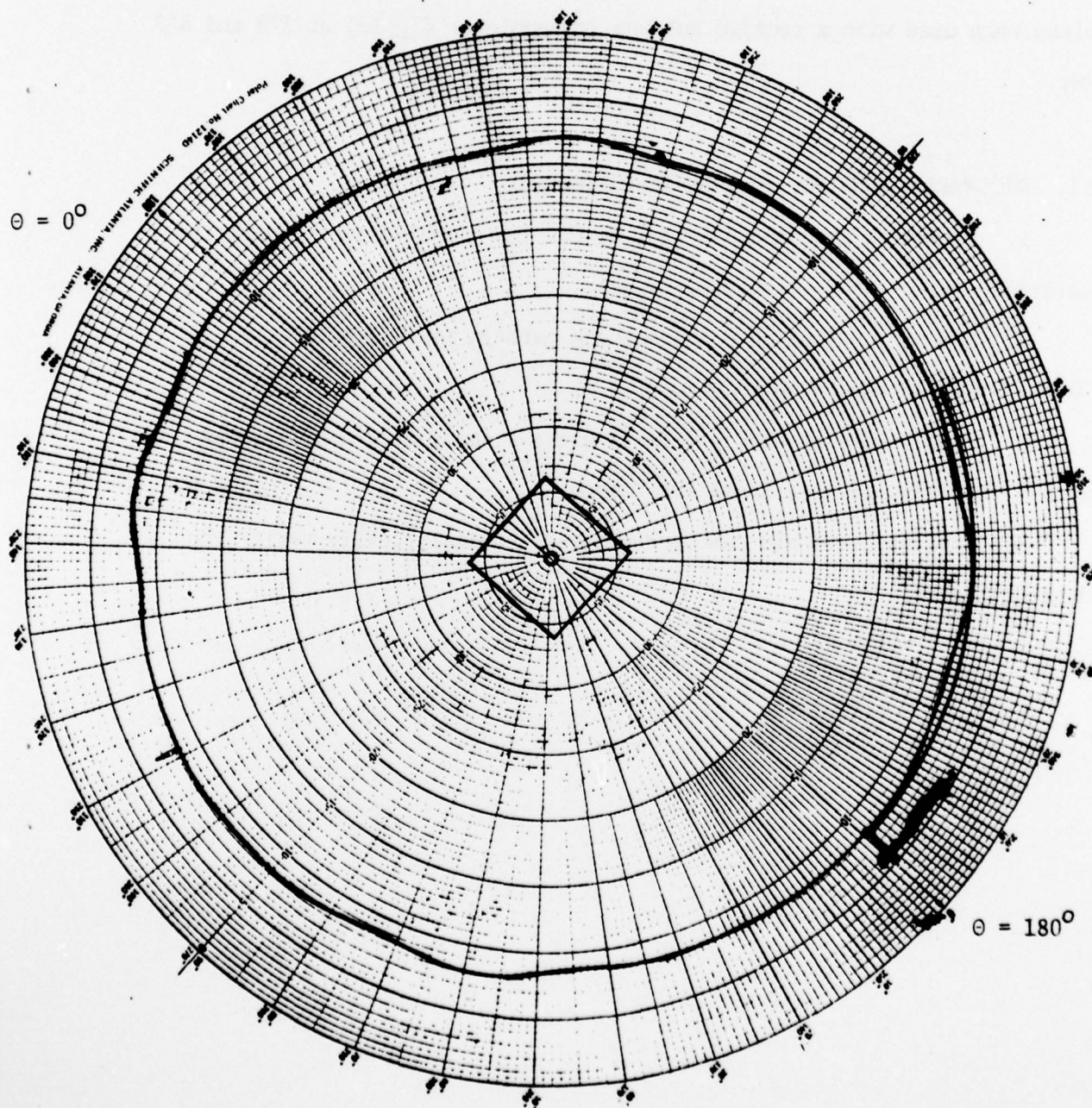


Figure 44. Monopole - Metal - 837 MHz

V. CONCLUSION

This effort has shown that a 50 ply piece of graphite epoxy composite material (material #332-94 by Fiberites) behaves as an aluminum ground plane when used with a receive antenna (monopole or dipole) at 370 and 837 MHz.

VI. RECOMMENDATIONS FOR FURTHER INVESTIGATION

1. Determine the conductivity, σ , for the graphite epoxy composite material.
2. Repeat the impedance and antenna pattern measurements at a lower frequency such that $\omega\epsilon = \sigma$.
3. Investigate shielding effects using a sheet of graphite epoxy with a thickness less than one skin depth, δ .
4. Utilize available computer programs to analytically verify the data collected.

VII. BIBLIOGRAPHY

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